Evaluation of Soil Stiffness Via Non-Destructive Testing

Final Report
June, 2001

Ohio Research Institute
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EVALUATION OF SOIL STIFFNESS VIA NON-DESTRUCTIVE TESTING

FINAL REPORT

Prepared in Cooperation with the

OHIO DEPARTMENT OF TRANSPORTATION and
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Introduction

1.1 General Statement

The premature failure of highway pavements from substandard construction practices and materials is a major expense in terms of money, labor, and natural resources, and improved techniques are needed to mitigate this problem. Knowing the structural characterization of subgrade and base materials used in pavement systems is essential for developing better design and construction procedures. Standard guides for the design of pavement structures incorporate the correlation between resilient modulus and more traditional soil parameters such as stiffness, density, moisture content and material type. Making accurate assessments of the structural condition of roads during construction helps tremendously in locating weak areas prone to localized failure and correcting them prior to completion of the pavement. Knowledge of these failure-prone zones greatly facilitates maintenance and rehabilitation operations.

After construction, it is generally assumed that pavements perform up to design standards. However, non-uniformity or variability in the structural characteristics of various pavement components and poor construction monitoring may lead to the formation of localized areas of premature distress in the form of rutting, cracking or other types of distress. Under repeated traffic loading and severe environmental conditions, these areas tend to deteriorate rapidly, leading to poor service conditions and necessitating early maintenance and rehabilitation. Recent studies have shown that the most effective method for controlling the premature failure of pavement is through proper inspection and in-situ testing of construction materials during construction [1].

Nondestructive testing (NDT) of the subgrade and base layers along the length of a project during and directly after construction aids in identifying localized problem areas where the stiffness of these materials deviates from the desired values. Dynamic response and pavement parameters, such as layer thickness, stiffness, modulus, moisture content, and density can be determined from NDT data. After calculating the variability in the characteristics of the subgrade and base material, potential problem areas can be identified and remedial measures taken during the construction process. By preventing premature distress, the overall service life of the pavement can be extended, thus conserving resources.

1.2 Existing Methods Ensuring Quality of Highway Construction

Pavement performance depends greatly upon the quality and variability of materials incorporated into the pavement structure. The careful monitoring of material quality and placement and the measured response of pavement layers during construction improves overall compliance to specifications and in-service performance of the pavement. Nondestructive testing procedures are the primary method used by the Strategic Highway Research Program (SHRP) for monitoring long-term pavement performance. While the use of deflection measurements to characterize base and subgrade structural capacity and to determine the elastic moduli of individual structural layers is becoming more widely accepted in the pavement community, the development of new equipment incorporating different techniques to measure this capacity has complicated the issue to some extent.

In addition to equipment that measures deflection from induced loads, nondestructive devices such as Nuclear Density Gauges are used to measure density (ASTM D2950). A long-standing correlation exists between subgrade stiffness and density, with higher density generally being indicative of higher stiffness, though moisture and soil type can dramatically affect this correlation. Nuclear gauge testing requires only ten minutes for density determination. By having density data available on site, engineers can estimate the degree of compaction and provide better control during construction. Nuclear density readings are, however, limited to the upper 300 mm of material and greatly affected by non-uniformity within the various pavement layers being tested. Despite this shortcoming, Nuclear Density Gauges are considered to be a viable tool for maintaining quality assurance of the subgrade and base when used in conjunction with other nondestructive testing methods.

1.3 Objectives

Pavement structural design generally assumes that subgrade and base layers will be constructed with certain expected in-situ properties or characteristics. The type and thickness of base material used is based on laboratory test results obtained for existing subgrade materials, expected traffic loads, and the environment in which the pavement will provide service. Deficiencies and variability within these design parameters in the field is a major cause of reduced pavement performance. The success of nondestructive testing methods in assessing pavement condition and predicting pavement performance depends upon the quality and the reliability of data obtained from the various NDT devices. Since each device has its own unique set of operational characteristics and output data, direct comparisons are necessary on a variety of materials to determine the capabilities and limitations of each NDT, and to compare their effectiveness in assessing performance.

The principal purposes of this investigation were to measure the structural characteristics of the subgrade and base on a section of US 35 with various NDT devices as the section was being constructed, and to compare the output of these devices in assessing structural conditions and variability. A series of nondestructive tests was conducted using a Nuclear Density Gauge, a Humboldt Stiffness Gauge, a German Plate Load Test, a Falling Weight Deflectometer (FWD), and a Dynamic Cone Penetrometer. All tests except for the German Plate Load test were conducted at 50-foot intervals along the driving lane of a 2000-foot-long test section after the subgrade and base were completed. The German Plate Load test was conducted at 100-foot intervals. Data obtained from these tests were used to compute soil parameters such as stiffness, unit layer load deflection, and layer moduli. The resilient modulus of the subgrade and base were determined in the laboratory according to the SHRP protocol.

Chapter 2

Project Background

2.1 Project Site Description

The 2000-foot long test section used for this project is a part of the new construction of eastbound US 35, undertaken by the Ohio Department of Transportation (ODOT). The project site is located in the village of Jamestown, Silver Creek Township, in Greene County. Construction work started at station 405+00 and ended at 683+00, spanning a distance of 5.265 miles. The section used for this project started at station 410+00 and ended at station 430+00.

This location was selected because of the presence of relatively uniform topographical and subsurface soil conditions. The pavement consisted of a four-lane divided highway comprised of 12-foot-wide lanes with a 10-foot-wide outside shoulder and a 6-foot-wide inside shoulder, having a pavement cross slope of 0.0156 ft/ft and shoulder cross slope of 0.0417 ft/ft. Figure 2.1 provides a map of the project site.

2.2 Subgrade

Subgrade material was collected from the site and tested in the laboratory for Atterberg's limit, sieve analysis and moisture content. The soil was found to have the following values:

Liquid limit = 22.8%	Plasticity index = 6.1%
Specific gravity = 2.4761	Plastic limit = 16.7%

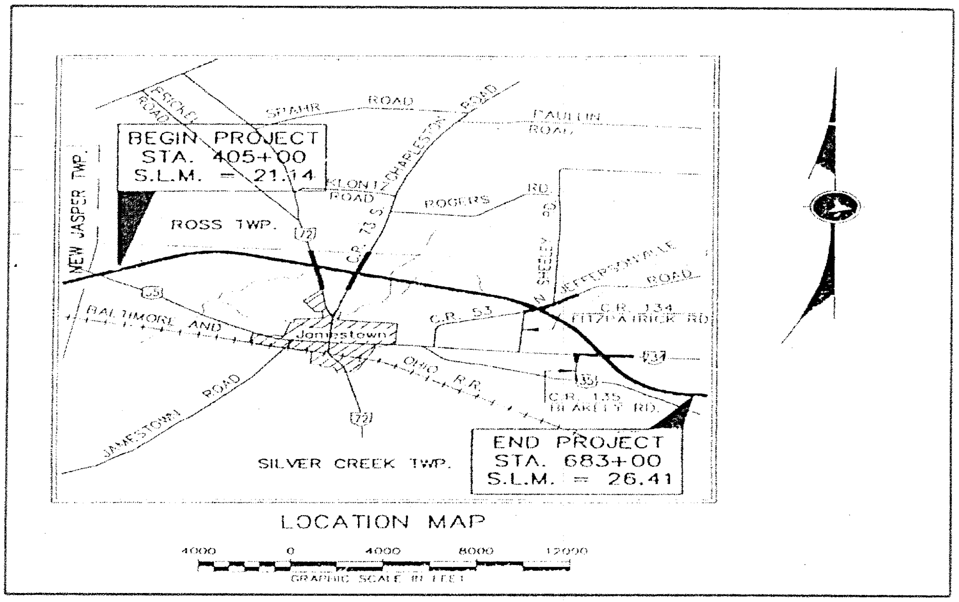


Figure 2.1: Site Location

By plotting the point where the plasticity index = 6.1% and the liquid limit = 22.8% in the plasticity chart, as shown in Figure 2.2, the soil falls in CL-ML sector as per the Unified Classification System. The soil was therefore classified as silty clay material.

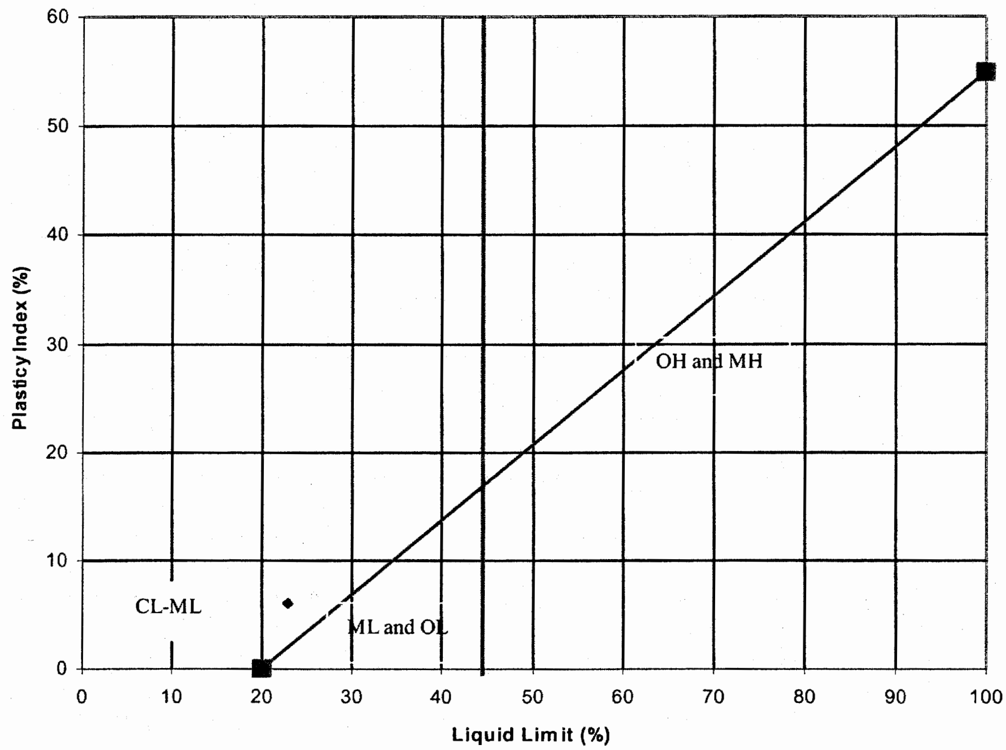


Figure 2.2: Plasticity Chart

Soil borings were examined at stations 418+00, 422+00 and 426+00. The results from these bore logs are summarized in Table 2.1.

Table 2.1: Soil Classification

Summary of Soil Test Stationing Along U.S 35										
Location	From -To	% AGG	%C.S	%F.S	% Silt	% Clay	L.L	P.L	W.C	Classification
	1.0 -2.5	Top soil							26	Visual
418+00	3.5- 5.0	1	2	6	31	60	39	20	26	A-6
	6.0-7.5	same as 3.5- 5.0							30	Visual
	8.5- 10.0	brown silt and clay, some sand							12	Visual
	13.5 - 15.0	same as 8.5 - 10.0							10	Visual
	1.0 -2.5	22	4	11	63		36	17	29	A-6
422+00	3.5- 5.0	mottled gray and brown silty clay, some gravel little sand							16	Visual
	6.0-7.5	same as 3.5- 5.0							16	Visual
	8.5- 10.0	same as 3.5- 5.0							19	Visual
	13.5 - 15.0	same as 3.5- 5.0							11	Visual
	1.0 -2.5	23	10	14	31	52	25	9	20	A-4
426+00	3.5- 5.0	brown sandy silt, some clay, little gravel							18	Visual
	6.0-7.5	same as 3.5- 5.0							28	Visual
	8.5- 10.0	same as 3.5- 5.0							16	Visual
	13.5 - 15.0	gray sandy silt, some clay							14	Visual

2.3 Initial Subgrade Moisture Content and Density

The initial moisture content and density for the subgrade was taken along the centerline and right wheelpath of the eastbound driving lane at 50-foot intervals with a Nuclear Density Gauge. The results are summarized in Table 2.2.

Table 2.2: Subgrade Density and Moisture Profile.

				Center Line of Drive Lane			Outside Wheel Path of Drive Lane		
Test Date	Project Station	Station	Test #	Dry Density(pcf)	% Moisture	Rod Depth (in)	Dry Density(pcf)	% Moisture	Rod Depth (in)
7/6/99	410+00	0+00	1	125.7	2.9	2	132.3	3.0	6
7/6/99	410+50	0+50	2	127.6	3.3	4	133.1	3.3	6
7/6/99	411+00	1+00	3	130.2	3.1	4	137.8	3.4	4
7/6/99	411+50	1+50	4	128.5	4.5	6	129.4	5.2	6
7/6/99	412+00	2+00	5	123.9	4.1	6	126.4	4.1	6
7/6/99	412+50	2+50	6	126.5	5.0	6	125.1	4.5	6
7/6/99	413+00	3+00	7	129.5	5.1	6	124.6	5.2	6
7/6/99	413+50	3+50	8	133.0	4.3	6	128.3	4.3	6
7/6/99	414+00	4+00	9	124.9	4.6	6	126.9	4.3	6
7/6/99	414+50	4+50	10	133.4	4.4	6	130.1	4.2	6
7/6/99	415+00	5+00	11	128.0	4.5	2	133.8	3.9	6
7/6/99	415+50	5+50	12	136.0	4.4	4	138.0	3.8	4
7/6/99	416+00	6+00	13	134.1	4.1	4	135.2	3.8	4
7/6/99	416+50	6+50	14	123.7	4.2	6	131.3	4.4	6
7/6/99	417+00	7+00	15	134.3	4.1	4	132.1	4.4	4
7/6/99	417+50	7+50	16	123.0	4.2	4	132.7	4.7	4
7/6/99	418+00	8+00	17	132.9	3.5	4	129.3	3.4	6
7/6/99	418+50	8+50	18	134.0	3.7	4	131.0	4.1	6
7/6/99	419+00	9+00	19	131.9	3.8	6	No Data		
7/6/99	419+50	9+50	20	134.6	3.9	6			
7/7/99	420+00	10+00	21	132.8	6.7	6	131.2	5.3	6
7/7/99	420+50	10+50	22	133.8	5.4	6	132.8	5.5	6
7/7/99	421+00	11+00	23	130.7	5.6	6	125.2	6.1	6
7/7/99	421+50	11+50	24	132.2	6.4	6	128.7	6.6	6
7/7/99	422+00	12+00	25	129.5	6.8	6	129.0	8.2	6
7/7/99	422+50	12+50	26	130.2	6.7	6	132.0	5.5	6
7/7/99	423+00	13+00	27	131.1	6.0	6	130.4	7.3	6
7/7/99	423+50	13+50	28	130.7	7.2	6	128.9	7.1	6
7/7/99	424+00	14+00	29	130.7	7.1	6	128.0	8.0	6

7/7/99	424+50	14+50	30	128.0	6.2	6	132.4	6.1	6
7/7/99	425+00	15+00	31	132.5	6.7	6	132.5	6.8	6
7/7/99	425+50	15+50	32	130.8	6.1	6	136.5	5.8	6
7/7/99	426+00	16+00	33	136.3	5.5	6	135.7	5.5	6
7/7/99	426+50	16+50	34	134.1	6.2	6	134.3	5.3	6
7/7/99	427+00	17+00	35	131.6	5.8	6	130.3	6.6	6
7/7/99	427+50	17+50	36	132.3	8.3	6	133.7	7.5	6
7/7/99	428+00	18+00	37	133.8	5.0	6	133.5	5.3	6
7/7/99	428+50	18+50	38	133.2	6.6	6	135.5	6.9	6
7/7/99	429+00	19+00	39	130.6	5.1	6	125.5	5.0	6
7/7/99	429+50	19+50	40	130.8	6.1	6	131.0	5.8	6
7/7/99	430+00	20+00	41	127.5	4.6	6	129.1	4.4	6

Each data point is the average of four one-minute readings taken at 90 degrees from one another.

The higher moisture readings recorded on 7/7/99 were due to rainfall the previous night.

2.4 Dense Graded Aggregate Base (DGAB)

The dense graded aggregate base used in this project conformed to the ODOT Item 304 specification. ODOT 304 is an aggregate base that consists of crushed carbonate stone, crushed gravel, crushed air-cooled slag, granulated slag, a mixture of crushed and granulated slag, or other types of suitable material. This base has a tightly graded aggregate structure without any gaps in the gradation. Table 2.3 shows the gradation specification for ODOT 304 base material. This gradation creates a very dense base material that can be easily compacted.

Table 2.3: ODOT 304 DGAB Distribution

Sieve	Total percent Passing
50 mm (2 inches)	100
25.0 mm (1 inch)	70-100
19.0 mm (3/4 inch)	50-90
4.75 mm (No.4)	30-60
600 μm (No.30)	9-33
75 μm (No.200)	0-13

2.5 Initial Moisture Content and Density Data

The initial moisture content and density for the base was taken along the centerline at regular intervals of 50 feet using a Nuclear Density Gauge. The results are summarized in Table 2.4.

Table 2.4. Base Density and Moisture Profile

				Center Line of Drive Lane			
Test Date	Project Station	Station	Test #	Dry Density (pcf)	% Moisture	Rod Depth (in)	Comment
8/4/99	410+00	0+00	1	127.5	1.5	6	
8/4/99	410+50	0+50	2	132.0	1.3	6	
8/4/99	411+00	1+00	3	132.9	1.3	6	
8/4/99	411+50	1+50	4	130.2	1.5	6	
8/4/99	412+00	2+00	5	133.1	1.5	6	
8/4/99	412+50	2+50	6	129.9	1.5	6	
8/4/99	413+00	3+00	7	130.1	1.4	6	
8/4/99	413+50	3+50	8	132.9	1.5	6	
8/4/99	414+00	4+00	9	128.8	1.4	6	
8/4/99	414+50	4+50	10	131.6	1.5	6	
8/4/99	415+00	5+00	11	132.4	1.2	6	
8/4/99	415+50	5+50	12	131.3	1.4	4	
8/4/99	416+00	6+00	13	127.5	1.4	4	
8/4/99	416+50	6+50	14	131.2	1.4	6	
8/4/99	417+00	7+00	15	136.3	1.3	6	
8/4/99	417+50	7+50	16	133.1	1.2	6	
8/4/99	418+00	8+00	17	134.3	1.2	6	
8/4/99	418+50	8+50	18	130.9	1.3	6	
8/4/99	419+00	9+00	19	123.6	1.3	4	Loose stone
8/4/99	419+50	9+50	20	133.0	1.4	6	
8/4/99	420+00	10+00	21	130.8	1.4	6	
8/4/99	420+50	10+50	22	127.9	1.2	6	
8/4/99	421+00	11+00	23	134.1	2.2	6	
8/4/99	421+50	11+50	24	127.4	1.4	4	
8/4/99	422+00	12+00	25	131.7	1.5	6	
8/4/99	422+50	12+50	26	129.7	1.4	6	
8/4/99	423+00	13+00	27	130.6	1.1	6	
8/4/99	423+50	13+50	28	132.5	1.3	6	
8/4/99	424+00	14+00	29	127.8	1.2	6	
8/4/99	424+50	14+50	30	128.2	1.1	6	
8/4/99	425+00	15+00	31	131.2	1.4	6	
8/4/99	425+50	15+50	32	131.2	1.2	6	
8/4/99	426+00	16+00	33	131.8	1.2	6	
8/4/99	426+50	16+50	34	130.3	1.2	6	
8/4/99	427+00	17+00	35	131.2	1.4	6	
8/4/99	427+50	17+50	36	125.3	1.3	6	
8/4/99	428+00	18+00	37	131.2	1.2	6	
8/4/99	428+50	18+50	38	130.7	1.2	6	
8/4/99	429+00	19+00	39	130.6	1.3	6	
8/4/99	429+50	19+50	40	124.4	1.7	6	Probably not compacted
			Average	**130.9**	**1.4**		
			Standard Deviation	**2.2**	**0.2**		

Each data point is the average of four one-minute readings taken at 90 degrees from one another.

2.6 Pavement design

The test section was constructed using 6.0 inches of Dense Graded Aggregate Base (DGAB, ODOT item 304), 4.0 inches of non-stabilized drainage base with filter fabric (ODOT item 307), and 9.0 inches of reinforced concrete (ODOT item 451).

Chapter 3

Field Testing Using Nondestructive Testing Techniques

3.1 Introduction

One of the most significant advancements in the field of pavement evaluation has been the development of nondestructive testing techniques (NDT), which are used to determine in-situ subgrade and base layer characteristics. NDT data enable the calculation of various pavement parameters that help in predicting pavement performance and also act as a guideline for undertaking maintenance and rehabilitation work.

The evaluation of subgrade and base stiffness using deflection-based NDT equipment involves the measurement of vertical deflection of the surface being tested as it deforms under an applied load. Subgrade and base parameters such as stiffness and elastic modulus can be calculated from these readings. Most current design procedures make use of deflection measurements and backcalculation techniques for determining pavement layer moduli.

Traditional laboratory methods used to determine the physical properties of paving materials, to develop construction specifications and to monitor construction activity have failed to incorporate the actual response of the pavement under actual wheel loads and to account for in-situ environmental conditions. These drawbacks of laboratory testing have led to significant advances in NDT testing on site during construction.

The nondestructive testing devices used for this investigation included:

a) Humboldt Stiffness Gauge

b) German Plate Load Test

c) Falling Weight Deflectometer

d) Dynamic Cone Penetrometer

3.2 Humboldt Stiffness Gauge

The Humboldt Stiffness Gauge (HSG) provides a simple, quick and accurate means of directly measuring stiffness of the upper lift of material. The stiffness of the subgrade and base is directly influenced by the degree of compaction, the moisture content of fine-grained material in these layers and the type of soil in the subgrade.

The HSG measures impedance at the soil surface by generating vibrations at 100 and 200 Hz that impart a very small change in the applied load [2]. The stiffness of the pavement material in resisting this load is determined at each frequency and the average is displayed on the Stiffness Gauge display window. The entire process takes about one minute. It has been found that, at low frequencies, the impedance at the surface is stiffness controlled. If a Poisson's ratio is assumed and knowing the HSG's physical dimensions, shear and elastic modulus can be derived for the base and subgrade. The HGS weighs about 10 kg, is 28 cm in diameter, 25.4 cm tall and rests on the soil surface via a ring–shaped foot, as shown in Figure 3.1.

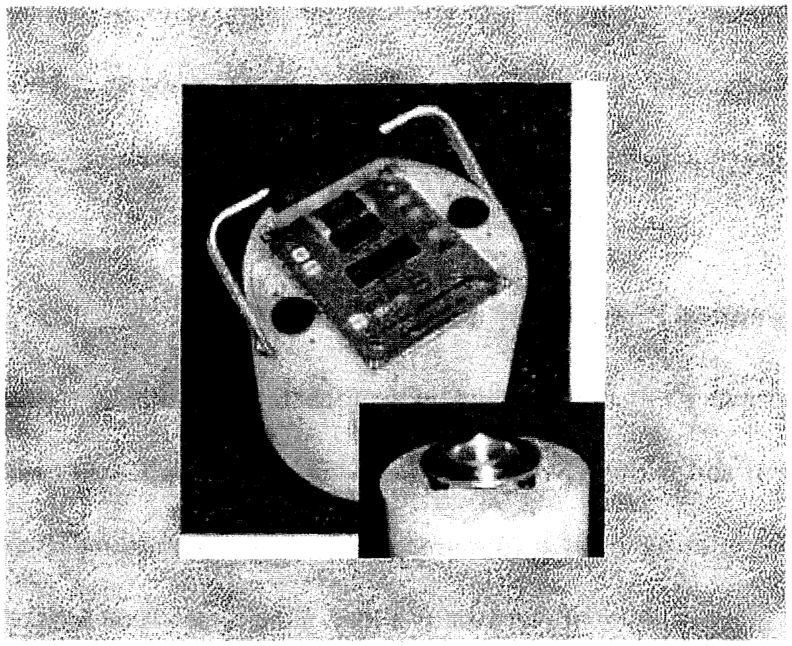


Figure 3.1: Humboldt Stiffness Gauge

Small deflections generated by the HSG are given the symbol δ, which is proportional to the outside radius of the ring foot (R), the elastic modulus (E), the shear modulus (G) and the Poisson's ratio (υ) of the soil. The stiffness of the layer being tested is the ratio of the force to the displacement: $K = P/\delta$. The HSG generates soil stress levels commonly experienced by the base and subgrade (192 Pa or 4 psi).

Test Procedure

The HSG was placed firmly on the soil surface, which itself required little or no preparation. A 60% minimum contact area between the HSG foot and soil was required. On particularly hard or rough surfaces, less than ¼ inch of moist sand or local fines was used to ensure adequate contact between the HSG and the surface, and to provide a uniform surface for the HGS. Once firm contact had been established, readings were taken by pressing the "Measure" button. Each stiffness reading took about one minute.

3.3. German Plate Load Test

German Plate Load testing is a procedure in which the sequential loading and unloading of soil is done by means of a load plate through a pressure application device [3]. Settlement of the plate is measured as the load is applied and released.

The Plate Load equipment consists of a load plate, a pressure application device with an oil pump, a single action hydraulic press, and a high–pressure hose. The load plates are made of steel of at least grade ST 52.0, and the bottom of the plate must be flat. A load plate with a diameter of 300 mm and a thickness of 25 mm was used for this project. A load application offset device (counter weight) producing a 10 KN load or greater is necessary to provide the required reaction: heavy trucks are most often used for this purpose.

The settlement measurement device used with the German Plate Load test consisted of a dial gauge conforming to DIN 878, with a scale gradation value of 0.01 mm and a minimum measurement range of 10 mm.

Test Procedure

Before beginning the Load Plate test, the area of ground selected for testing was made as flat and level as possible and loose particles were removed. The plate had to properly rest on the surface with no cavities below the plate. The area of contact between the plate and the soil surface had to be more than 60%. Figure 3.2 shows the set-up of the German plate load test.

The loading setup is shown in Figure 3.3. Each level of load was sustained for an equal time increment. A change in load between loading stages was completed in less than one minute. In the load relief stage, the load was removed from the plate in three stages of 50%, 25% and 0% of the maximum applied load. A second loading cycle was applied only after the complete load removal from the earlier loading sequence. This comprised one load application cycle. Settlement measurements for each load increment and load relief cycle were taken using the dial gauge.

Drawbacks of the German Plate Test include the lengthy time required to complete each test. The deflections being measured, which include material creep, are static and do not accurately represent the response of the pavement structure to moving vehicles.

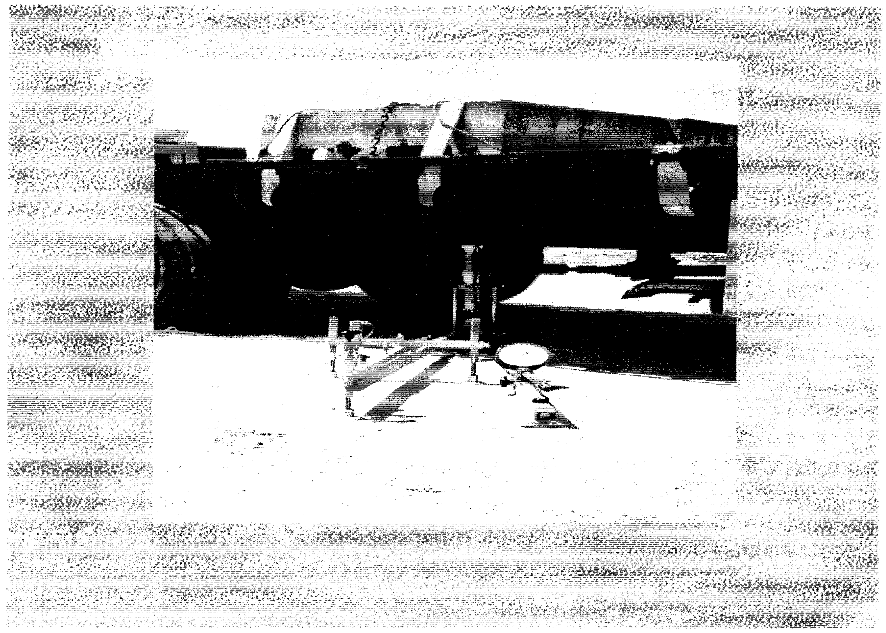


Figure 3.2: Assembly of the German Plate Load Device.

Figure 3.3: Load Application using the German Plate Load Test.

3.4 Falling Weight Deflectometer (FWD)

The Falling Weight Deflectometer (FWD) is a nondestructive testing device widely used for pavement testing, research and construction monitoring. Many test programs have been established to monitor subgrade construction and pavement performance by using the Falling Weight Deflectometer as the primary tool for assessing changes in layer properties and stiffness.

The Falling Weight Deflectometer (FWD) delivers a transient force impulse to the pavement layers by raising a weight to the desired height on a guide system and dropping it onto the 300-mm diameter circular footplate. By varying the mass of the weight or the drop height or both, the impulse load on the layer surface can be varied between 30 kn. and 110 kn. for standard FWDs, such as that used by ODOT, and between 30 kn. and 250 kn. for heavy-duty FWDs. Between four and nine sensors measure the deflection of the layer surface induced by the applied impulse load. The first sensor is mounted at the center of the footplate, while the remaining sensors are positioned at various radial distances up to 2.5 meters from the load center. All recorded peak deflections are displayed on the FWD monitor and stored for subsequent downloading.

The Model 8000 Dynatest Falling Weight Deflectometer (FWD) used for this research weighs about 2500 pounds and is a trailer-mounted NDT device capable of being towed by a suburban type vehicle or truck at regular highway speed. The FWD is pictured in Figure 3.4. The transient pulse-generating device consists of a trailer-mounted frame capable of directing different sets of mass configurations to fall from a predetermined height at right angles to the surface.

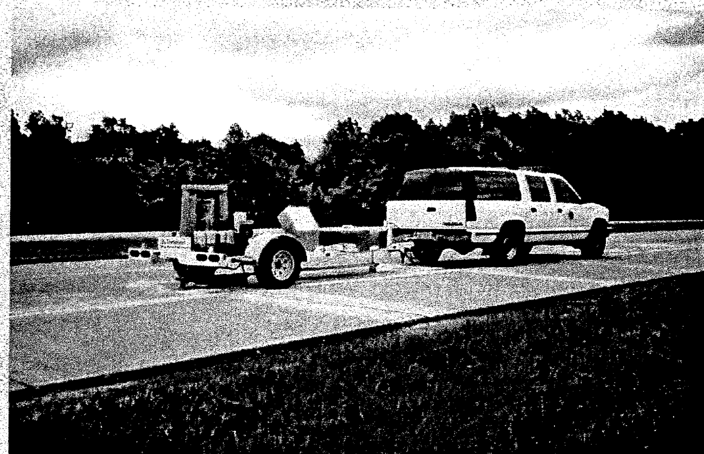


Figure 3.4: Trailer Mounted Falling Weight Deflectometer.

Test Procedure

The FWD device was positioned at the test point. The footplate and seven sensors spaced 0, 8, 12, 18, 24, 36, and 60 inches away from the center of the loaded area were then lowered onto the layer being tested, as shown in Figure 3.5. Pressure was applied by dropping the desired weight from a selected height. After the data had been recorded, the device was moved to the next site. A typical test cycle requires about one minute to complete.

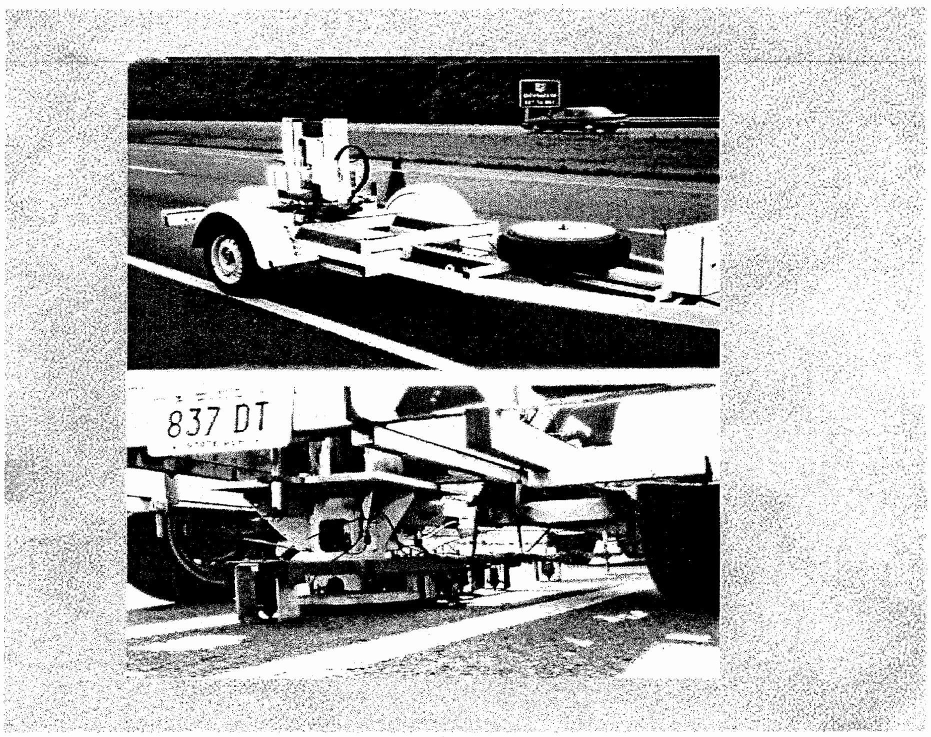


Figure 3.5: The FWD Sensors

3.5 Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (DCP) is a quick, simple, automated field test method for evaluating the in-situ stiffness of existing highway pavements. The greatest advantage associated with the DCP is its ability to penetrate into underlying layers and accurately locate zones of weakness within the pavement structure. It measures the strength and stiffness of unstabilized base and subgrade layers. The unit has software for storing DCP data.

Test Procedure

The Dynamic Cone Penetrometer (DCP), shown in Figure 3.6, generates sufficient energy to drive a rod up to 1.2 m into the pavement structure by striking the head of the rod with an 8-kilogram weight falling a distance of 574.0 mm. The rate of penetration is continuously monitored with depth. Measuring the stiffness of each layer gives a clear profile of the underlying support layers. While the resistance to a driven rod may not be indicative of the actual load-carrying capacity of the layers, weaknesses within the layered structure can be quickly identified. When the DCP rate of penetration exceeds established criteria, a zone of weakness is indicated. Testing the subgrade to a depth of 1.2 m requires about five minutes.

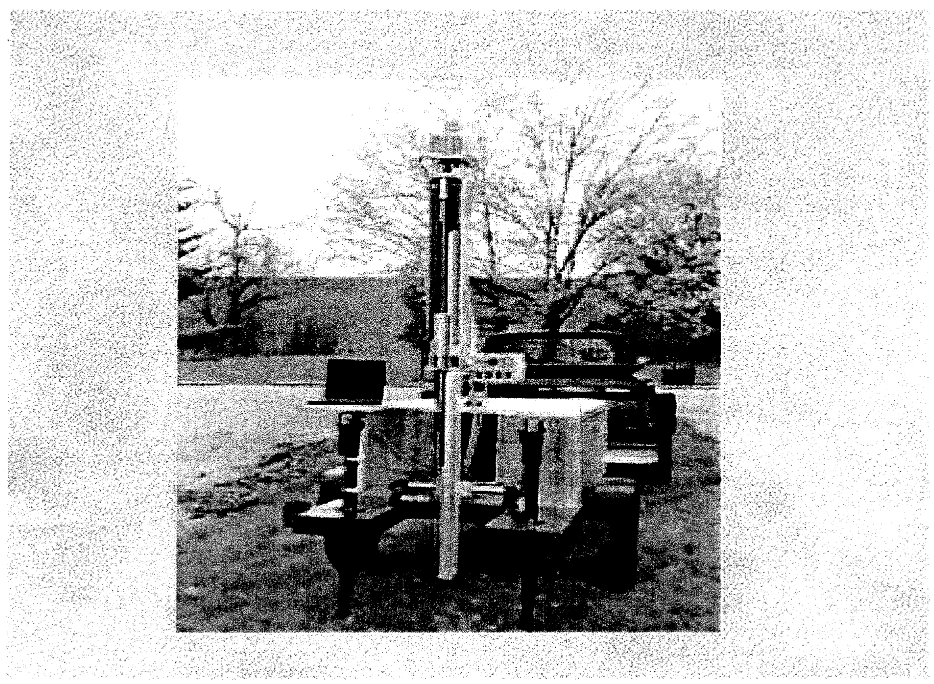


Figure 3.6: Dynamic Cone Penetrometer

3.6 Laboratory Testing

The laboratory test procedures utilized in this investigation complied with standard SHRP PROTOCOL P-46.

Equipment

Resilient modulus tests were conducted in the OU-ORITE laboratory. Tests were performed using the resilient modulus test system, which has a sophisticated triaxial chamber, an Electro-servo controlled actuator, computer signal conditioning, load command generation and a data acquisition system. The load was applied from the top using the closed loop electrohydraulic testing machine with a function generator. The haversine-shaped load pulse was applied in repeated cycles consisting of a 0.1 second load duration and a 0.9 second rest period. The detailed methodology of conducting the resilient modulus test of unbound granular base/subbase materials and subgrade soils can be found in SHRP PROTOCOL P46.

Test Procedure

The resilient modulus of the subgrade material was determined by applying confining pressures of 6 psi, 4 psi and 2 psi for five sequences, each consisting of 100 cycles. Table 5.6 in chapter 5 lists the resilient modulus, bulk stress, applied deviator stress, moisture content and dry density at which the tests were performed. The subgrade material was tested twice to check the repeatability of the results.

Resilient modulus tests on the base material were performed by applying confining pressures of 3 psi, 5 psi, 10 psi, 15 psi and 20 psi for three sequences of 100 cycles. The tests were performed twice to ensure consistent results.

Chapter 4

Analysis of Field Data

4.1 Humboldt Stiffness Device

During testing of the subgrade and base materials in the field, four separate readings were taken and averaged together for the subgrade and base at 50-foot intervals. The stiffness value obtained at each location, which was directly displayed in the Humboldt Stiffness Gauge display window, was recorded in MN/m.

Stiffness values were computed with the Humboldt Stiffness Device using the following equation:

$$K = P/\delta \approx 1.77\ RE\ /\ (1-\upsilon^2) \qquad (4.1)$$

Where,

K = stiffness (lb./in)
P = load in pounds
δ = Deflection

After calculating the stiffness (K), knowing the radius (R), and assuming Poisson's ratio (υ) = 0.4, the modulus (E) can be calculated with Equation 4.2. Since the influence zone for the Stiffness Gauge is limited to a 6–inch depth, the modulus of compacted subgrade and base materials must be calculated from data obtained on the surface of those layers.

$$E = \frac{K(1-\upsilon^2)}{1.77\,R} \qquad (4.2)$$

Where,

E = Modulus
K = stiffness
R = radius of the HSG ring = 2.25 inches
υ = Poisson's ratio = 0.4
P = load in pounds

4.2 German Plate Load Test

Raw deflection data collected with the German Plate Load device are summarized in Appendix B. Settlement measured on the subgrade and base at each loading and unloading sequence was utilized for calculation purposes. Stiffness (lb./in), modulus (psi), and unit load layer deflection were calculated from the raw data using Equations 4.3 - 4.8 for both the first sequence of loading and also for the second sequence of loading.

The subgrade and the composite stiffness of the entire base layer, which includes the depth of the subgrade required to support the applied load test, were calculated using the equation $K = \frac{P}{\delta} = \frac{\pi R E_3}{2(1-\nu^2)}$ (4.3)

The subgrade modulus for the Plate Load Test device was computed using

$$E = \frac{2K(1 - V^2)}{\pi R} \quad (4.4)$$

Equations 4.5 – 4.7, which were used to evaluate the modulus of a two-layer system of base and subgrade directly under the center of the loading plate, were obtained from the concept of Odemark and Boussinesq [4], which is also known generally as the "method of equivalent thickness". This method consists of transforming a system of *n* layers of different layer moduli into a single layer of equivalent stiffness where all layers have the same modulus. When calculating the base modulus for the German Plate Load Test and the Falling Weight Deflectometer, the influence of the applied load, which extends to a great depth into the subgrade layer, makes it necessary to adopt the method of equivalent thickness to calculate the modulus of the base layer.

For a two-layer system of base and subgrade, the deflection $D_{0,2}$, located directly under the center of the load plate on the top of the base, was approximated using equation 4.5.

$$D_{o,2} = 2(1-\nu^2)\frac{qa}{E_3 E_2}[E_3 + F_b(E_2 - E_3)] \qquad (4.5)$$

Where,

D_0 = deflection (inches)
q = pressure (psi)
a = radius (inches)
E_2 = Base modulus (psi)
E_3 = Subgrade modulus (psi)
F_b = Boussinesq Deflection Factor, calculated using Equation 4.6.

$$F_b = \left[\sqrt{\left(1+\left[\frac{h_e}{a}\right]^2\right)} - \left(\frac{h_e}{a}\right)\right]\left[1+\left(\left(\frac{h_e}{a}\right) \div \left(2(1-\nu_2)\sqrt{1+\left(\frac{h_e}{a}\right)^2}\right)\right)\right] \qquad (4.6)$$

Where,

$h_e =$ equivalent thickness of subgrade to replace base in inches in order to maintain the stiffness equivalent to that of the base, determined using Equation 4.7.

$$h_e = h_2 \left(\frac{E_2}{E_3} \right)^{1/3} \tag{4.7}$$

Where,

h_2 = thickness of base (inches)
E_2 = base modulus
E_3 = subgrade modulus

The unit load layer deflection on the subgrade and base material along the centerline at each station was calculated using Equation 4.8:

$$\text{Unit deflection} = \frac{\mathrm{L}}{\mathrm{P}/\mathrm{A}} \tag{4.8}$$

Where,

δ is the deflection measured at the site
P is the load applied in pounds (lb.)
A is the area of the circular steel plate in inches squared (in^2)

4.3 Falling Weight Deflectometer

Deflection measurements for each set of FWD drops were recorded using seven geophones placed at various distances from the center of the loaded area. Deflections measured at the center of the load plate were used to calculate modulus and stiffness. These parameters were calculated using Equations 4.3 – 4.8, which were also used for the German Plate Load test.

4.4 Dynamic Cone Penetrometer (DCP)

The DCP drives the penetrometer rod into the ground using constant energy for each blow, and the penetration index determined with the DCP is calculated as a running depth of penetration per blow. After determining the penetration index, Equations 4.9 and 4.10 were used to calculate CBR and the subgrade and base modulus (M_R). From these equations two modulus values were obtained. The upper limit value was calculated by adding 0.075 and the lower value was obtained by subtracting 0.075, as shown in equation 4.9.

$$\log(CBR) = 2.200 - 0.71(\log PI)^{1.5} \pm 0.075 \tag{4.9}$$

Where PI = DCP Penetration Index (mm/blow)

$$M_R = 1.2\ CBR \tag{4.10}$$

Chapter 5

Test Results and Discussion

This chapter presents stiffness, modulus, and unit deflection results calculated from data obtained from three different NDT devices and the Dynamic Cone Penetrometer, as well as laboratory tests. Tables presented here record the stiffness and elastic modulus values of the subgrade and base layers in the test section on US 35 selected for this project. Figures are included to show graphically how the stiffness and modulus of the subgrade and base layers vary along the length of the section.

Tables 5.1 and 5.2 summarize the stiffness and elastic modulus values for the subgrade and base layers, as calculated from data obtained via the Humboldt Stiffness Gauge, the German Plate Load Test and the Falling Weight Deflectometer (FWD). The subgrade and base stiffness values for all the NDT devices were calculated using equation 4.3. The subgrade and base modulus values for the Stiffness Gauge were computed using equation 4.2. The subgrade modulus values for the German Plate Load test and the Falling Weight Deflectometer were calculated using equation 4.4. In calculating the base modulus with the data from these devices, the "method of equivalent thickness" approach was followed using equations 4.5 through 4.7. The iterative method that was followed in calculating the base modulus for the Falling Weight Deflectometer and the German Plate Load test is presented in Appendices B and C.

For the German Plate Load test, the stiffness and elastic modulus of the subgrade and base layers were calculated using deflection data measured while the maximum normal stress was applied to the plate, which was approximately 4600 lb.

It should be noted here that deflection data were recorded by the Falling Weight Deflectometer at load ranges of 3500 - 4500 lb. and 6500 – 9000 lb. Subgrade and base modulus and stiffness were calculated for both load ranges.

Table 5.1: Stiffness and Modulus of Subgrade

Station	Stiffness Gauge		FWD (Large Load)		FWD (Small Load)	
	Stiffness Lb./in	Modulus Ksi	Stiffness Lb./in	Modulus Ksi	Stiffness Lb./in	Modulus Ksi
410.00	143482	30.30	970864*	87.92*	1167681*	105.75*
410.50	139990	29.51	591197	53.54	445534	40.35
411.00	171955	36.32	955051*	86.49*	933120*	84.50*
411.50	83772	17.77	360942	32.69	298820	27.06
412.00	92590	19.52	607598	55.02	700000	63.39
412.50	80418	17.02	99260	8.99	101226	9.17
413.00	81722	17.26	175891	15.93	165517	14.99
413.50	78455	16.56	156588	14.18	161785	14.65
414.00	67428	14.25	99004	8.97	85407	7.74
414.50	97187	20.59	181447	16.43	183634	16.63
415.00	115286	24.37	628769	56.94	465902	42.19
415.50	112989	23.81	499590	45.24	382735	34.66
416.00	116717	24.68	1519928*	137.65*	1115954*	101.06*
416.50	81774	17.29	74397	6.74	66206	6.00
417.00	127325	26.93	747601	67.70	722677	65.45
417.50	78049	16.51	413512	37.45	349495	31.65
418.00	112376	23.77	606602	54.93	534676	48.42
418.50	104815	22.12	299136	27.09	299932	27.16
419.00	88554	18.73	105527	9.56	105066	9.52
419.50	106393	22.42	201184	18.22	225190	20.39
420.00	57691	12.23	79353	7.19	75279	6.82
420.50	83873	17.76	567467	51.39	331328	30.01
421.00	70856	14.92	86512	7.84	86761	7.86
421.50	65770	13.93	124207	11.25	134051	12.14
422.00	57773	12.25	48670	4.41	58989	5.34
422.50	45825	9.72	47554	4.31	59656	5.40

423.00	84537	17.83	114271	10.35	114190	10.34
423.50	100270	21.12	87943	7.96	78036	7.07
424.00	82740	17.52	40014	3.62	38654	3.50
424.50	71788	15.18	41119	3.72	44147	4.00
425.00	44133	9.31	59957	5.43	55661	5.04
425.50			161052	14.59	164716	14.92
426.00			703720	63.73	755594	68.43
426.50			142784	12.93	167411	15.16
427.00			61486	5.57	61094	5.53
427.50			64828	5.87	20251	1.83
428.00			204505	18.52	193723	17.54
428.50			45188	4.09	30423	2.76
429.00			56412	5.11	29623	2.68
429.50			54456	4.93	30600	2.77
430.00			268021	24.27	292593	26.50
Mean	**91824**	**19.40**	**234415**	**21.23**	**213594**	**19.34**
V	**0.30**	**0.30**	**1.10**	**1.10**	**1.10**	**1.10**

Notes:

- FWD and Stiffness Gauge readings were taken at 50-foot intervals.
- Because of a low battery, Stiffness Gauge readings could not be obtained beyond Station 425+00 on the subgrade.
- V- Coefficient of Variation
- * - These values are considered to be outliners and were omitted from the Mean and V calculations

Table 5.2: Composite Base Layer Stiffness and Modulus of Base

Station	Stiffness Gauge		FWD (Large Load)		FWD (Small Load)	
	Stiffness Lb./in	Modulus Ksi	Stiffness Lb./in	Modulus Ksi	Stiffness Lb./in	Modulus Ksi
410.00	104959	22.11	568274	22.00	575558	14.00
410.50	120061	25.33	354557	14.00	319625	16.00
411.00	155505	32.82	610561	22.00	456017	11.00
411.50	131034	27.66	267095	15.00	200624	8.00
412.00	135464	28.64	250500	3.30	293032	6.00
412.50	124648	26.35	127726	13.50	158458	30.00
413.00	125603	26.52	258677	40.00	190563	22.00
413.50	152871	32.26	260826	45.00	228596	35.00
414.00	112598	23.71	333305	200.00*	310334	250.00*
414.50	128276	27.12	226141	22.00	207747	22.00
415.00	110185	23.22	366219	22.00	383710	22.00
415.50	151581	32.03	465108	45.00	498162	60.00
416.00	132700	28.08	320720	2.50*	838650	35.00
416.50	118870	25.16	431421	500.00*	581172	650.00*
417.00	164798	34.85	595471	32.00	670408	40.00
417.50	206145	43.53	544913	70.00	639551	135.00
418.00	204278	43.15	514039	35.00	575000	95.00
418.50	169117	35.72	288834	22.00	330736	32.00
419.00	110990	23.43	189704	35.00	205966	65.00

419.50	115198	24.31	343846	65.00	334515	55.00
420.00	134249	28.31	355930	225.00*	332026	550.00*
420.50	85316	18.05	453850	22.00	541838	95.00
421.00	119106	25.10	192922	75.00	206294	90.00
421.50	136942	28.92	129313	12.50	122552	10.00
422.00	132223	27.91	148274	60.00	136138	55.00
422.50	119934	25.36	128773	40.00	128827	50.00
423.00	138921	29.32	231708	50.00	245328	100.00
423.50	118661	25.06	94754	8.00	95745	13.00
424.00	101580	21.42	96061	25.00	96396	50.00
424.50	85603	18.18	94280	20.00	102413	45.00
425.00	108214	22.85	79903	10.00	80924	15.00
425.50	120228	25.42	195812	20.00	225714	40.00
426.00	110344	23.33	310824	5.00	378455	18.00
426.50	122099	25.85	261674	65.00	285945	60.00
427.00	127477	26.96	181411	80.00	202950	160.00
427.50	103263	21.82	150291	28.00	27283	4.50
428.00	119159	25.11	320448	50.00	405686	120.00
428.50	158705	33.51	148700	45.00	137583	190.00*
429.00	114721	24.23	158615	40.00	138519	195.00*
429.50	63239	13.33	41586	2.50*	38623	5.50
Mean	**127372**	**26.90**	**277327**	**32.79**	**298192**	**46.69**
V	**0.22**	**0.22**	**0.60**	**1.10**	**0.70**	**1.00**

Notes:
- FWD and Stiffness Gauge readings were taken at 50-foot intervals.
- V- Coefficient of Variation.
- * - These values are considered to be outliers and were omitted from the Mean and V calculations.

Table 5.3: Stiffness and Modulus with the German Plate

Station	Subgrade				Base			
	First Sequence		Second Sequence		First Sequence		Second Sequence	
	Stiffness Lb./in	Modulus Ksi	Stiffness Lb./in	Modulus Ksi	Stiffness Lb./in	Modulus Ksi	Stiffness Lb./in	Modulus Ksi
410.50	243464	22.05	292100	26.45	72138	1.00	224680	20.00
411.50	307534	27.85	324556	29.39	64924	0.50	265545	25.00
412.50	44947	4.07	75218	6.81	94244	40.00	162278	55.00
413.50	58121	5.26	111925	10.14	153767	90.00	307474	130.00
414.50	114571	10.38	134318	12.16	52051	1.00	231328	50.00
415.50	282083	25.55	296913	26.89	49182	0.25	446133	60.00
416.50	22388	2.30	42642	3.86	88151	150.00*	198755	225.00*
417.50	254050	23.01	307474	27.85	77909	1.00	292100	30.00
418.50	172704	15.64	194733	17.64	92748	2.50	324556	60.00
419.50	119248	10.80	129822	11.76	64210	2.00	354061	185.00

420.50	235069	21.29	235056	21.29	89894	1.50	292100	55.00
421.50	81155	7.35	76868	6.96	33396	0.65	71791	5.00
422.50	11733	1.06	23183	2.10	36982	30.00	77893	60.00
423.50	19875	1.80	41141	3.73	40012	15.00	74897	20.00
424.50	11390	1.03	20972	1.90	22657	8.00	46961	15.00
425.50	66399	6.01	92730	8.40	73715	6.50	152338	30.00
426.50	41120	3.72	78493	7.11	91855	32.00	240225	32.00
427.50	10623	0.96	30372	2.75	39216	40.00	94226	65.00
428.50	14256	1.29	47218	4.28	37627	18.00	99141	30.00
429.50	486928*	44.09*	1947333*	176.00*	26425	0.10*	56269	0.15*
Mean	**111091**	**10.07**	**134512**	**12.18**	**65055**	**16.11**	**200638**	**51.50**
V	**0.93**	**0.93**	**0.79**	**0.79**	**0.47**	**1.44**	**0.57**	**0.84**

Note:

- V- Coefficient of Variation.
- * - These values are considered to be outliers and were omitted from the Mean and V calculations.

Figures 5.1 and 5.2 graph variations in subgrade and base stiffness resulting from non-uniformity in the material properties of these layers and the different nondestructive testing methods.

The stiffness values in figures 5.1 and 5.2 for the subgrade and base layers show generally lower stiffness values for the German Plate Load test and the Stiffness Gauge as compared to the Falling Weight Deflectometer. The lower German Plate results could be due to disturbance of the in-situ properties of the soil as the load plate was being seated and the static nature of the loads being applied. By applying a small load over a small contact area, the effectiveness of the Stiffness Gauge is limited to the upper six inches of the layer being tested. Overburden pressure tends to cause layers at greater depth to have higher stiffness values. Due to the six-inch depth measurement limitation, the Stiffness Gauge does not register these high stiffness values.

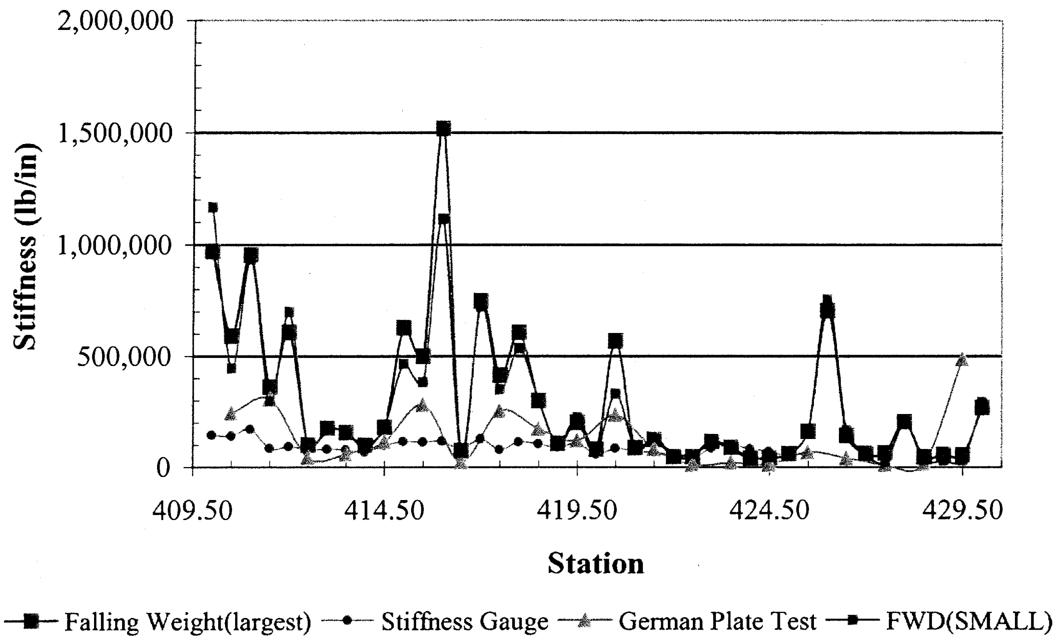


Figure 5.1: Subgrade Stiffness Plot

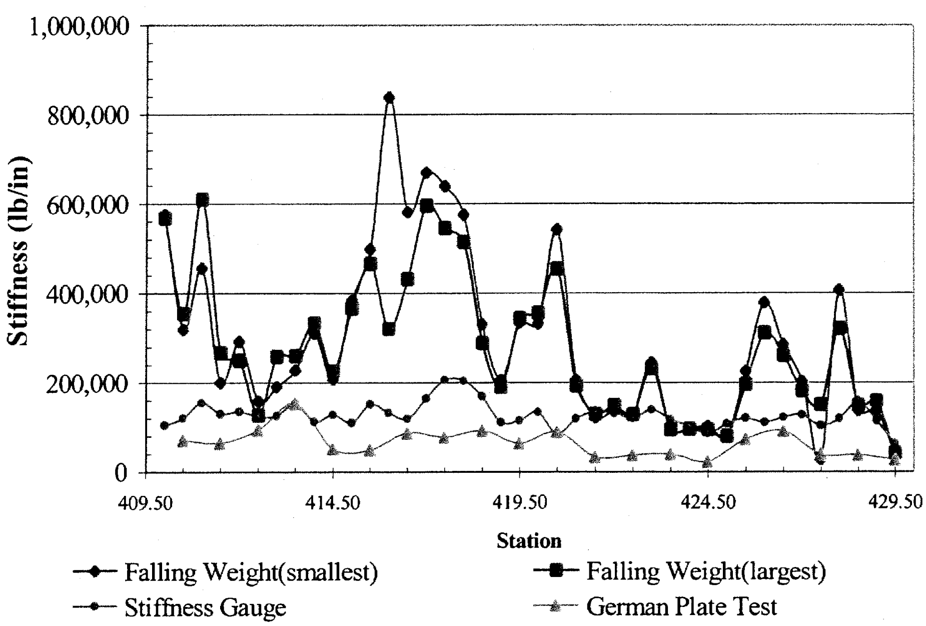


Figure 5.2: Stiffness Data for Composite Base Layer

Figure 5.3 compares subgrade and base moduli measured with the Stiffness Gauge along the length of the test section. As the graph shows, the base modulus values were consistently higher than the subgrade moduli, except between stations 410+00 to 411+00. The Falling Weight Deflectometer, German Plate test and Dynamic Cone Penetrometer results also showed lower base moduli in this same area. The plots indicate that the subgrade layer is stiffer from station 410+00 to station 411+00.

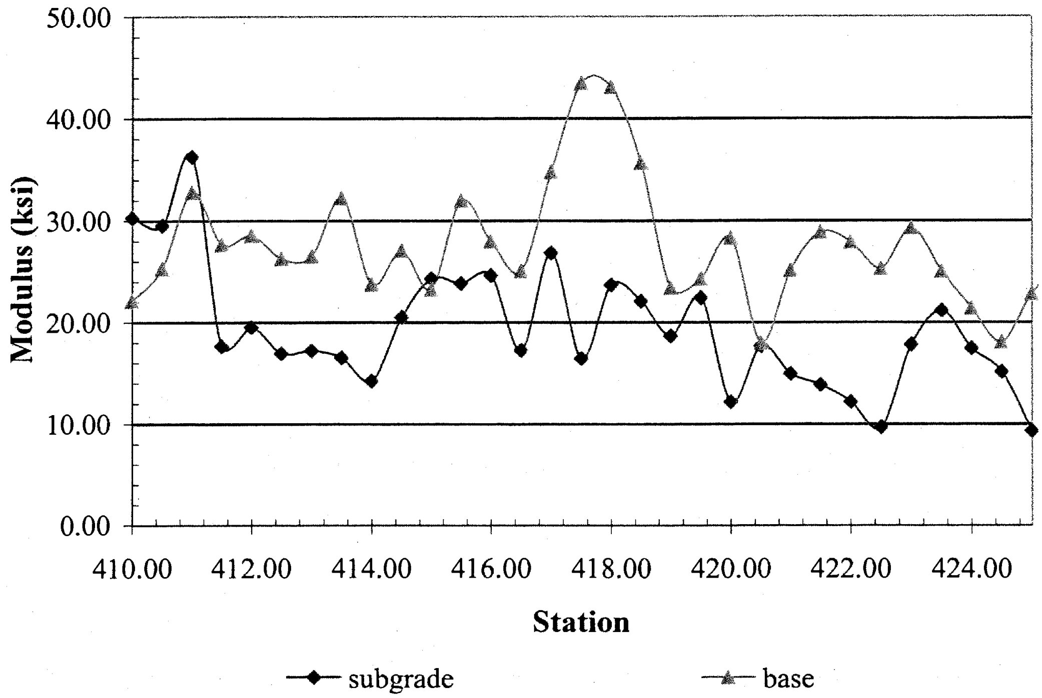


Figure 5.3: Subgrade and Base Modulus Values for the Stiffness Gauge

To compare the extent of variability in the subgrade and base moduli observed from the results of the German Plate Load test, these values of both the loading cycles were plotted along the section length, as shown in Figure 5.4a and 5.4b. From these graphs, it can be observed that the subgrade moduli are more uniform and higher in the first loading cycle than the base moduli. The lower base moduli in the first cycle may have resulted from poor surface contact between the load plate and the rough surface of the base layer. But the base modulus values obtained from second cycle are more realistic and seem to represent the in-situ properties.

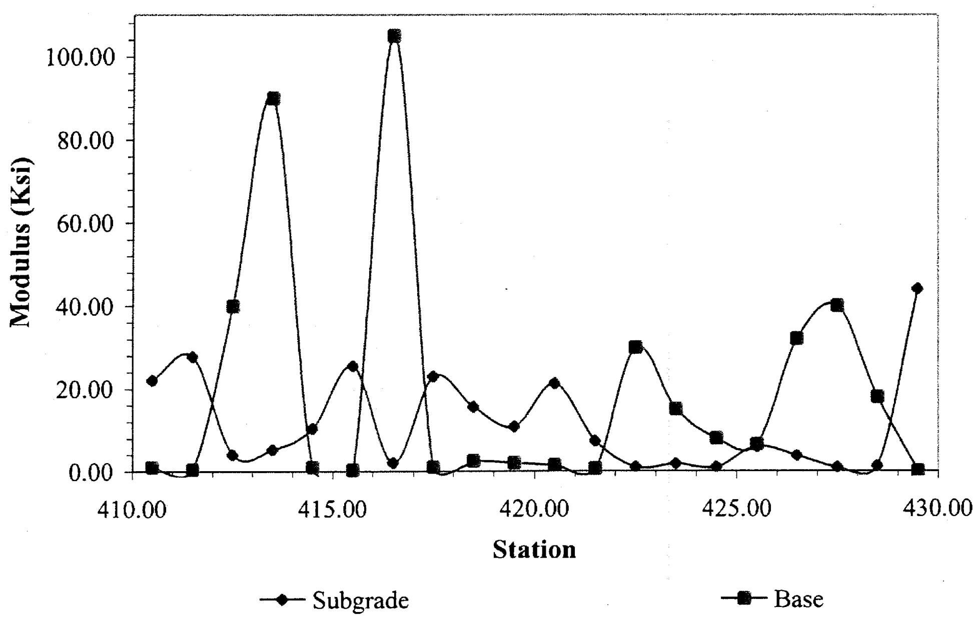


Figure 5.4a: Modulus values of first cycle For German Plate Load Test.

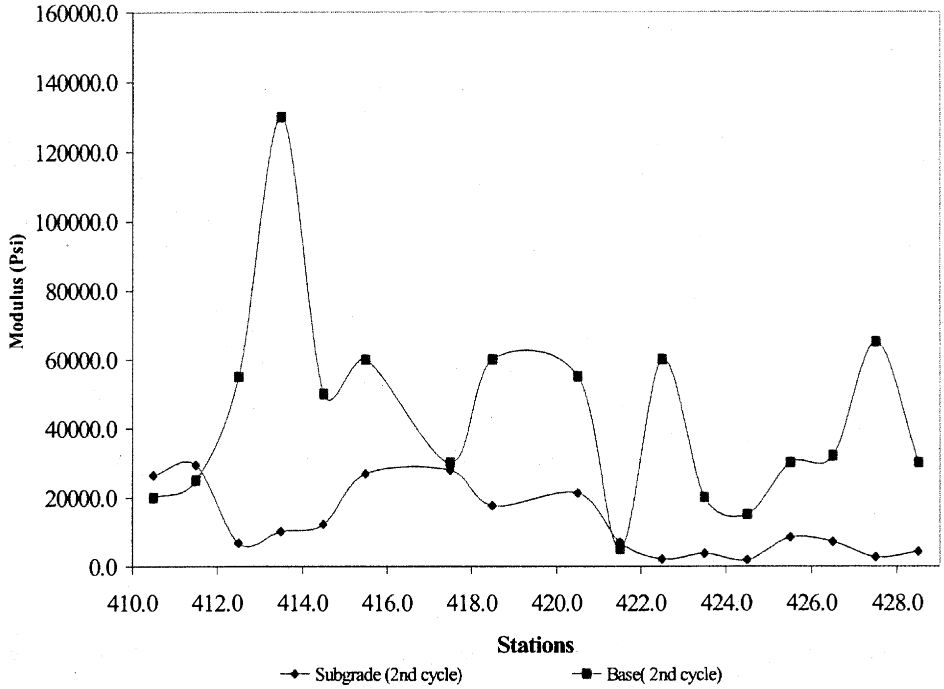


Figure 5.4b: Modulus values of second cycle For German Plate Load Test.

Figures 5.5a and 5.5b give a comparison of subgrade and base moduli along the test section, as calculated from data obtained with the Falling Weight Deflectometer at two load levels. In general, the base moduli were higher than the subgrade moduli, with occasional exceptions, including the entire 200-foot length between stations 410+00 and 412+00.

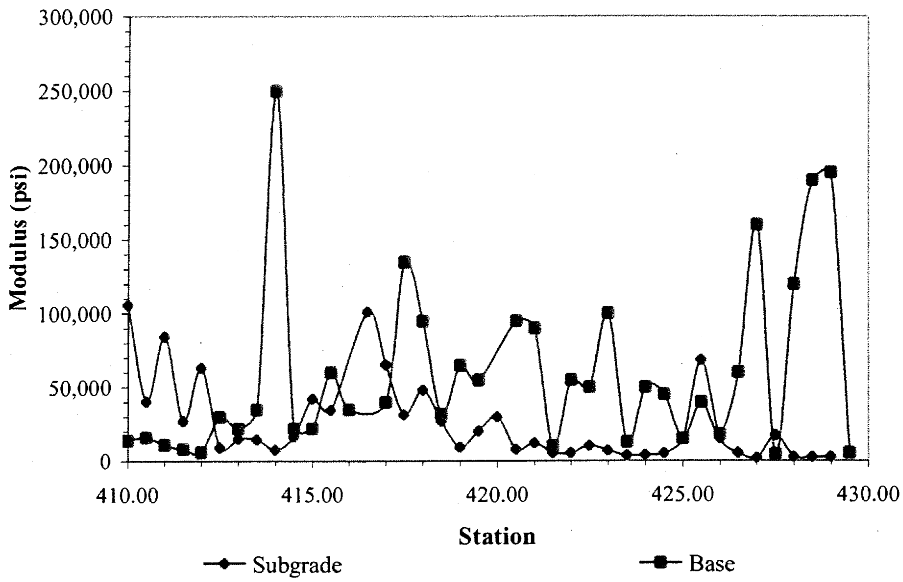


Figure 5.5a: FWD (Small Load) Modulus Values for Subgrade and Base

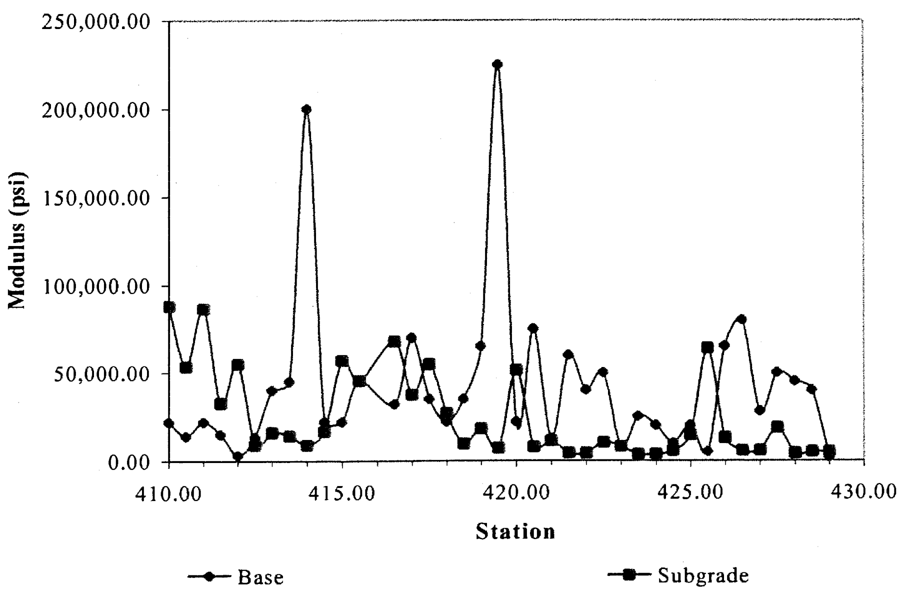


Figure 5.5b: FWD (Large Load) Modulus Values for Subgrade and Base

Graphs of the Dynamic Cone Penetrometer test results showing variations in the subgrade and base modulus with depth at each station along the test section are presented in Appendix B. Figures 5.6a-b are presented here, however, to illustrate the variation of the resilient modulus of the subgrade and base at station 420+00. These graphs show very low modulus values, which indicate the presence of weak subsurface conditions. The Falling Weight subgrade and base modulus values obtained at station 420+00 also are relatively smaller. Proper care should be taken at these locations to compact the layers in order to correct the weakness. Subgrade and base modulus values were calculated from the DCP data using equations 4.9 and 4.10. As mentioned in chapter 4, two sets of modulus values for subgrade and base showing the upper and lower limits for the values were calculated from Equation 4.9.

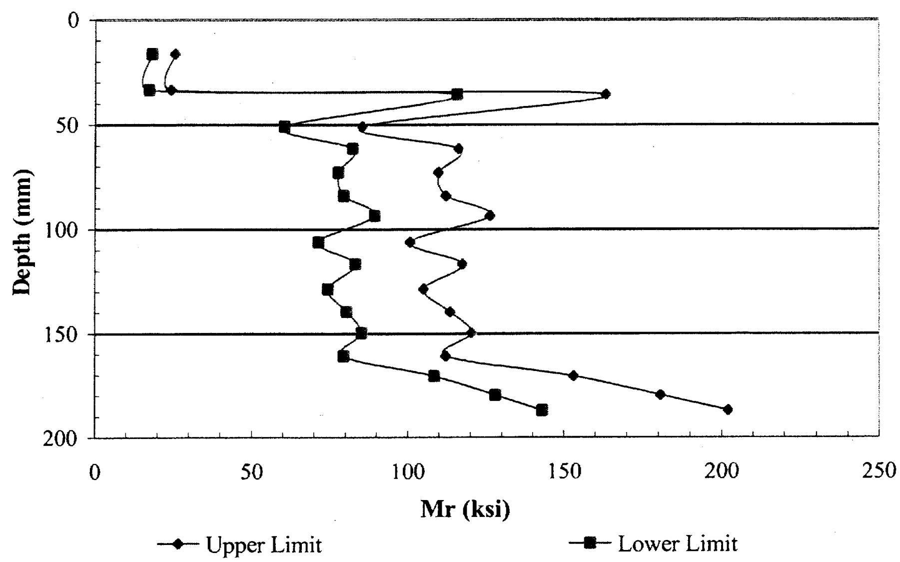
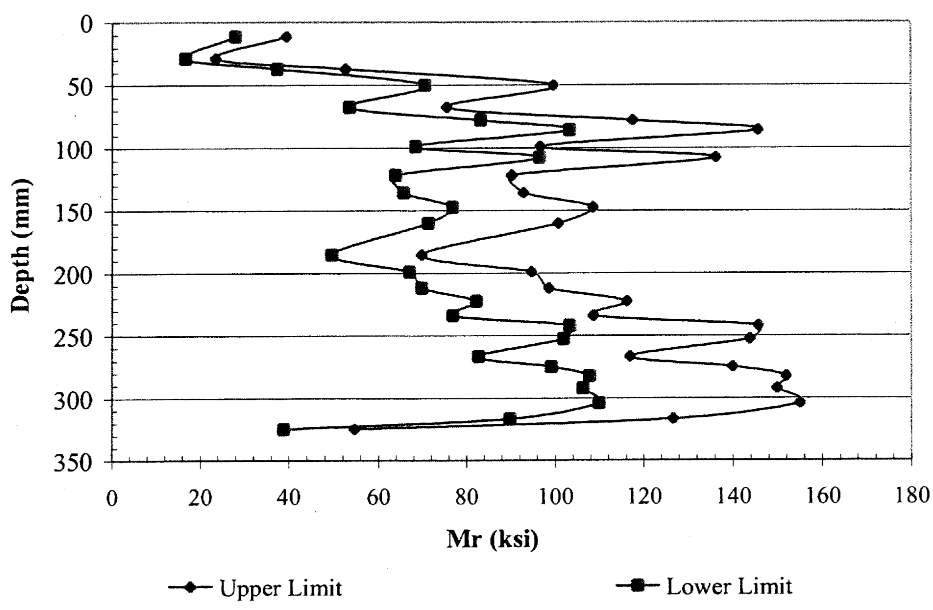


Figure 5.6a: Subgrade Modulus versus Depth at Station 420+00



Note: The base layer is comprised of 6 inches of standard 304 DGBA.

Figure 5.6b: Base Modulus versus Depth at Station 420+00

Figures 5.7a and 5.7b depict the variation in unit deflections of the subgrade and base layers computed using the Falling Weight Deflectometer and the German Plate Load test data. These graphs plot the unit deflections at each station along the length of the test section. The unit deflection for each layer was calculated using equation 4.8.

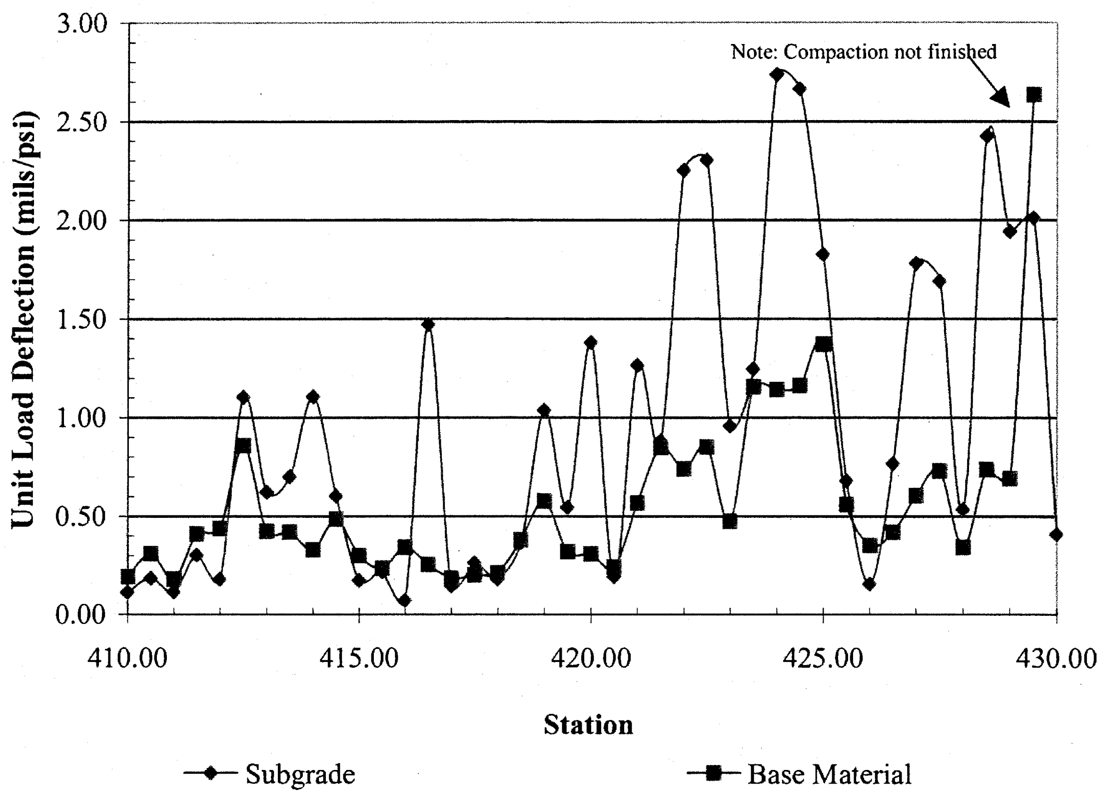


Figure 5.7a: Normalized FWD Deflection with Large Load

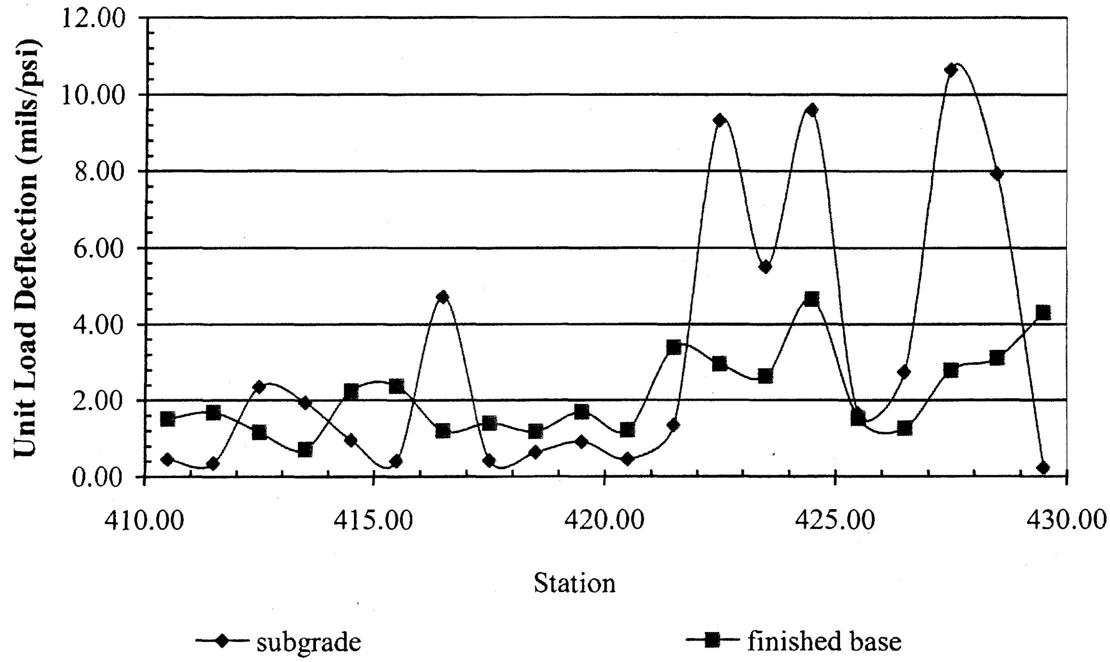


Figure 5.7b: Normalized Deflection from German Plate Load Test

Field Test Results

The calculated elastic modulus for the Stiffness Gauge and the German Plate Load test, as presented in Tables 5.1 and 5.2, ranged from 0.1 – 105 ski, whereas the elastic modulus calculated using the Falling Weight Deflectometer ranged from 2 to 250 ski. This difference in the modulus values results obtained from several nondestructive devices is primarily due to the difference in the magnitude and the nature of load applied by each type of NDT device. The Stiffness Gauge and German Plate Load test, devices that apply a small magnitude load that is more static in nature, fail to record the response of the subgrade and base properties at greater depths, whereas the dynamic load applied by the Falling Weight Deflectometer allows the response of the layers to be measured to a greater depth. This is why different devices provide dramatically different stiffness responses at the same location on the pavement structure. If the upper layer has been compacted to a greater stiffness than the lower layers, NDT devices using lighter loads should give higher in-situ stiffness than devices applying heavier loads. Conversely, heavier loads will give higher stiffness measurements than lighter loads when the underlying layers are stiffer than the top layer.

Figures 5.1, 5.2, 5.5a, 5.5b and 5.7a, which summarize the response of the Falling Weight Deflectometer along the section length, and Figures 5.6a and 5.6b, which show the Dynamic Cone Penetrometer response at station 420+00, clearly denote lower subgrade and base stiffness values and elastic modulus values along stations 419+50 through 424+50. Figure 5.7a-b, which show the unit deflection at each station, illustrate higher subgrade and base deflection between station 419+50 and 424+50. These high deflections, coupled with poor stiffness and modulus values along this 500-foot section, indicate lower strength of the subgrade and base layers. This calls for proper remedial measures to avert premature distress along this test section.

The moisture, dry density and stiffness data for the subgrade and base layers are plotted in Figures 5.8a-b and 5.9a-b. Figures 5.8a and 5.8b indicate that higher moisture contents produced lower subgrade stiffness values, irrespective of high dry density. The moisture content of the base did not vary much along the test section. Figures 5.9a-b show that higher stiffness values resulted when moisture content was lower and dry density higher.

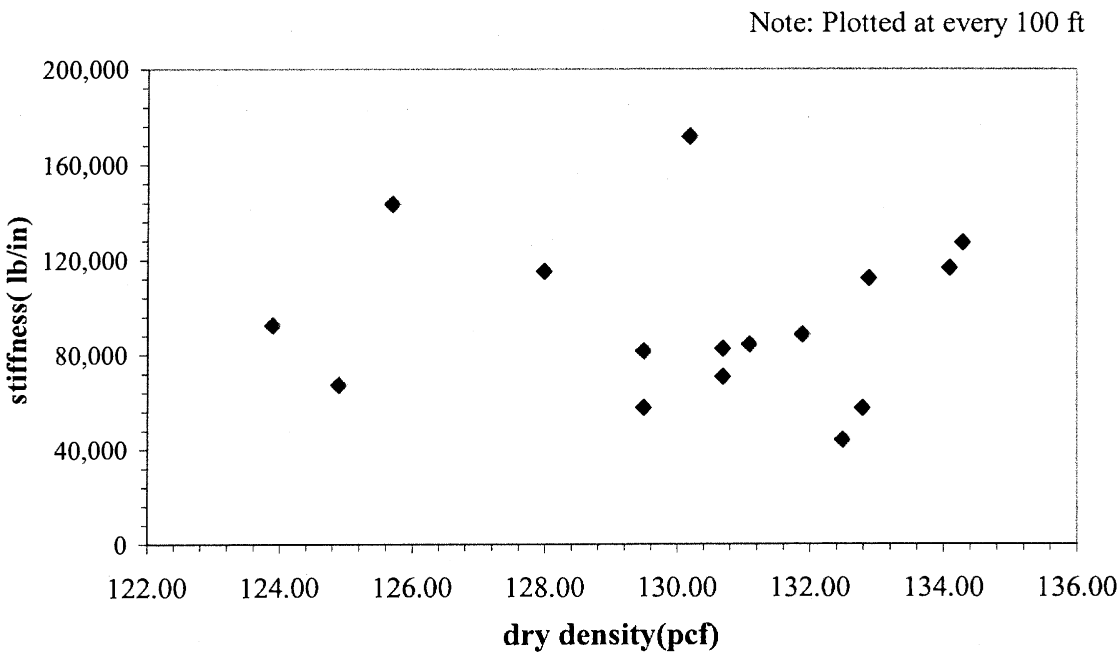


Figure 5.8a: Relationship between Subgrade Stiffness and Dry Density

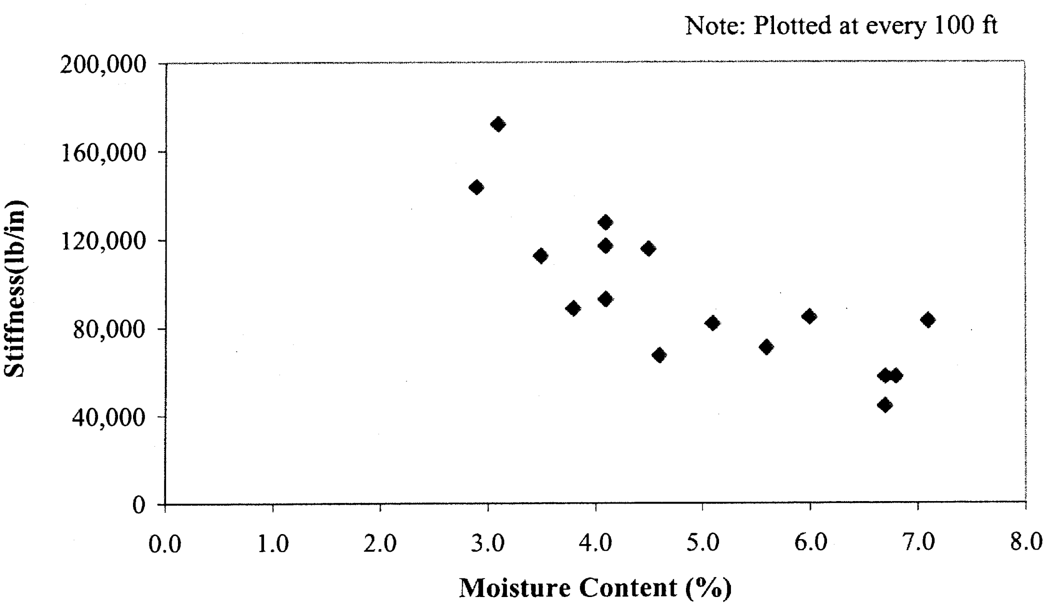


Figure 5.8b: Relationship Between Subgrade Stiffness and Moisture Content

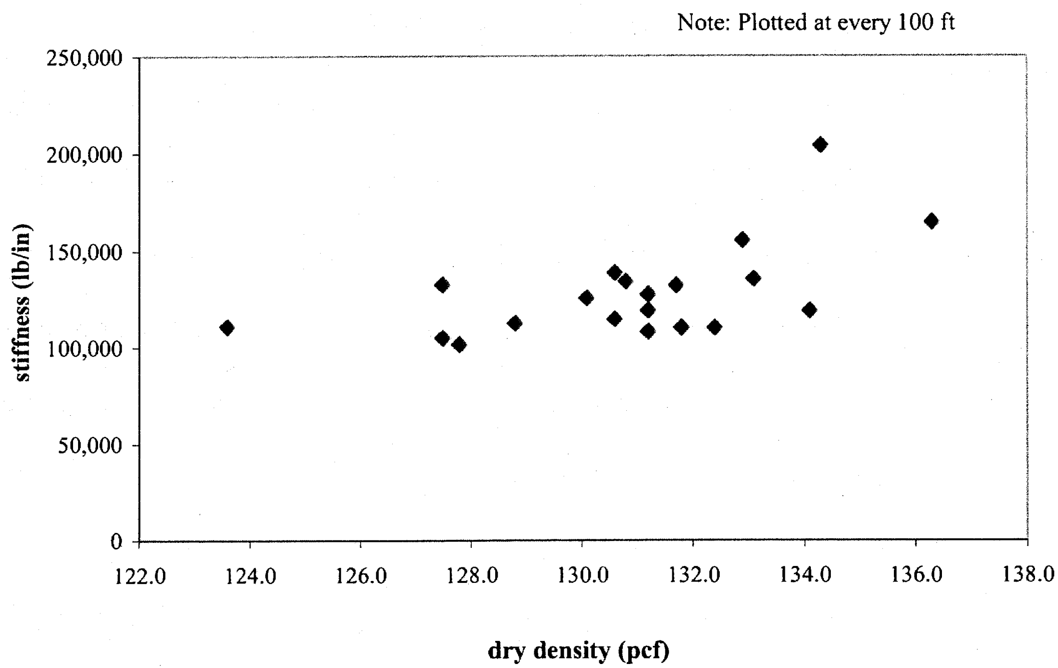


Figure 5.9a: Relationship between Base Stiffness and Dry Density

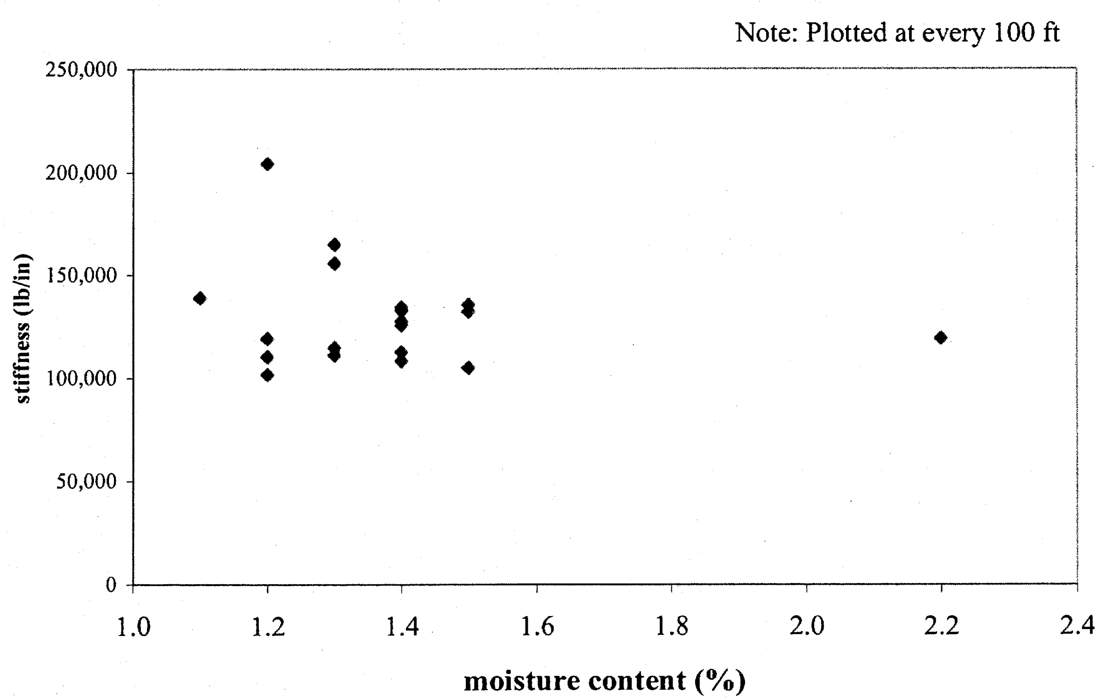


Figure 5.9b: Relationship between Base Stiffness and Moisture Content

Laboratory Resilient Modulus Test Results

Resilient modulus is defined as the ratio of deviatoric stress caused by the moving traffic loads to the recoverable strain. The resilient modulus property of the pavement material describes the resilient deformation and the state of stresses the pavement layers experience under traffic loads. In order to study the effect of stress on the deformation of the pavement materials, several graphs of bulk stress versus resilient modulus for subgrade and base layer are presented here.

The results of the laboratory tests on the subgrade are summarized in Table 5.6. The moisture content, dry density and sequence in which the confining pressures were applied during the test are also given.

Table 5.4a: Resilient Modulus Test Summary for Subgrade Soil (A-6)

Moisture Content = 5.8%(Lab.), 4.4 % (Field)
Laboratory Dry Density=136.5 pcf
Field Dry Density = 136.0 pcf
Station 415+50

Confining Pressure Psi	Applied Deviator Stress Psi	Bulk Stress Psi	Resilient Modulus Psi
6.0	2.998	20.998	13953.0
6.0	6.008	24.008	14420.0
6.0	8.968	26.968	14116.0
6.0	11.476	29.476	13125.0
6.0	14.033	32.033	12785.0
4.0	2.862	14.862	16824.0
4.0	5.997	17.997	13467.0
4.0	8.587	20.587	13189.0
4.0	11.558	23.558	12812.0
4.0	14.017	26.017	12148.0
2.0	2.726	8.726	19789.0
2.0	6.466	12.466	12208.0
2.0	9.159	15.159	12453.0
2.0	11.721	17.721	12103.0
2.0	14.344	20.344	12034.0

Table 5.4b: Resilient Modulus Test Summary for Subgrade Soil (A-6)

Moisture Content = 8.5% (Lab.), 6.7 % (Field)
Laboratory Dry Density = 128.5 pcf
Field Dry Density = 130.2 pcf
Station 422+50

Confining Pressure Psi	Applied Deviator Stress Psi	Bulk Stress Psi	Resilient Modulus Psi
6.0	2.618	20.618	12136
6.0	5.841	23.841	9946
6.0	8.287	26.287	8879
6.0	10.617	28.617	8178
6.0	12.861	30.861	7868
4.0	2.59	14.59	12239
4.0	5.841	17.841	9347
4.0	8.143	20.143	8346
4.0	10.531	22.531	7873
4.0	12.861	24.861	7781
2.0	2.532	8.532	12403
2.0	5.778	11.778	9021
2.0	8.085	14.085	8092
2.0	10.387	16.387	7822
2.0	12.861	18.861	7478

Figures 5.10a and 5.10b illustrate the relationship between Resilient Modulus and bulk stress for the subgrade layer.

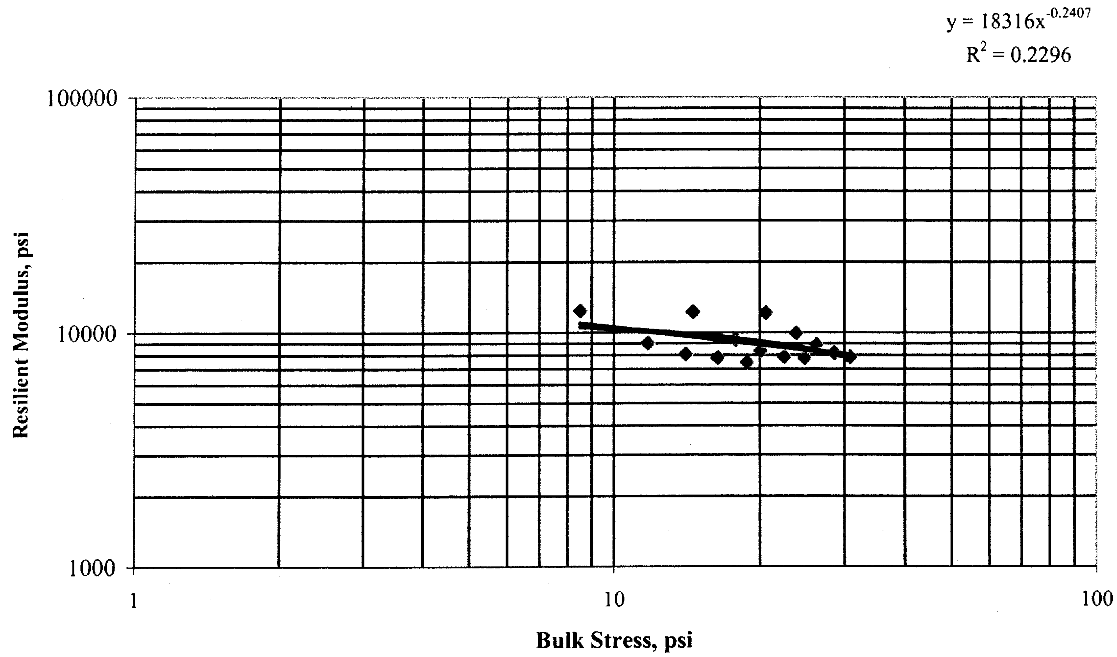


Figure 5.10a: Relationship between Resilient Modulus and Bulk Stress

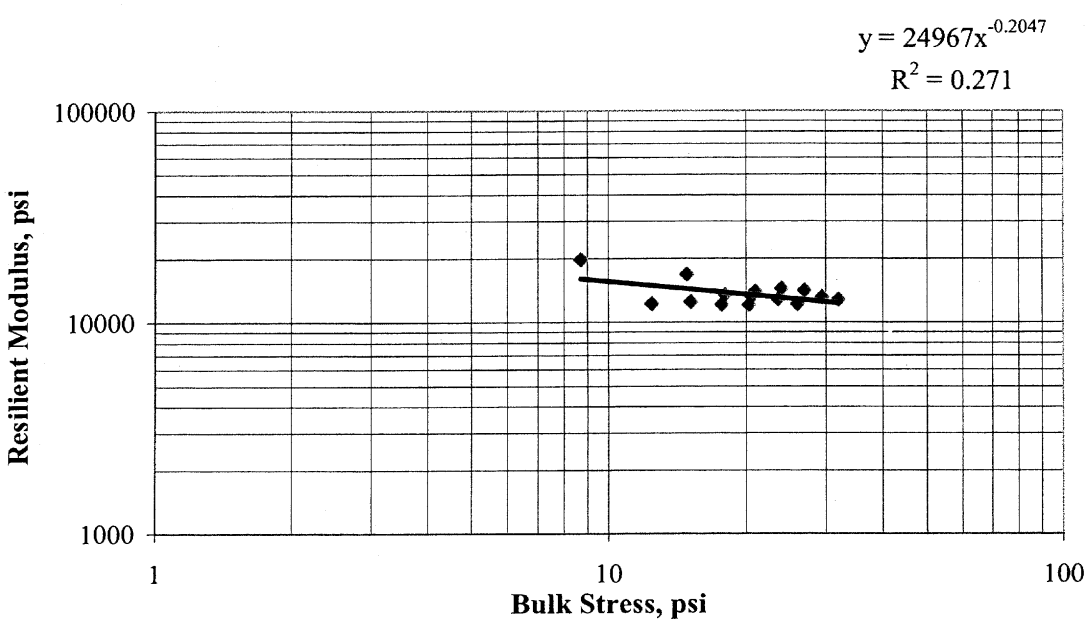


Figure 5.10b: Relationship between Resilient Modulus and Bulk Stress.

The Resilient Modulus test results for the base material are summarized in tables 5.5a and 5.5b.

Table 5.5a: Resilient Modulus Test Summary for Base Material

Moisture Content = 1.2% (Lab.) 1.2%(Field)
Field Dry Density = 132.04 pcf
Laboratory Dry Density = 130.0 pcf
Station = 415+ 00

Confining Pressure Psi	Applied Deviator Stress Psi	Bulk Stress Psi	Resilient Modulus Psi
3.0	4.156	13.156	7973
3.0	8.222	17.222	8962
3.0	12.079	21.079	9563
5.0	6.745	21.745	9630
5.0	13.072	28.072	10671
5.0	19.285	34.285	11318
10.0	12.949	42.949	12700
10.0	24.535	54.535	14612
10.0	34.635	64.635	16673
15.0	12.792	57.792	14073
15.0	18.782	63.782	15312
15.0	34.339	79.339	19080
20.0	18.524	78.524	16590
20.0	24.172	84.172	17864

Table 5.5b: Resilient Modulus Test Summary for Base Material

Moisture Content = 1.2% (Lab.) 1.4% (Field)
Field Dry Density = 129.7 pcf
Laboratory Dry Density=131.0 pcf
Station = 422+50

Confining Pressure Psi	Applied Deviator Stress Psi	Bulk Stress Psi	Resilient Modulus Psi
3.0	4.223	13.223	7791
3.0	8.321	17.321	8546
3.0	12.087	21.087	7244
5.0	6.611	21.611	8771
5.0	13.224	28.224	9453
5.0	19.603	34.603	9343
10.0	12.914	42.914	11822
10.0	24.93	54.93	13230

10.0	33.326	63.326	14505
15.0	11.896	56.896	11954
15.0	17.783	62.783	13177
15.0	33.27	78.27	17069
20.0	17.389	77.389	14268
20.0	22.546	82.546	15315

Figures 5.11a and 5.11b highlight the increase in resilient modulus values for the base layer with the steady increase in bulk stress.

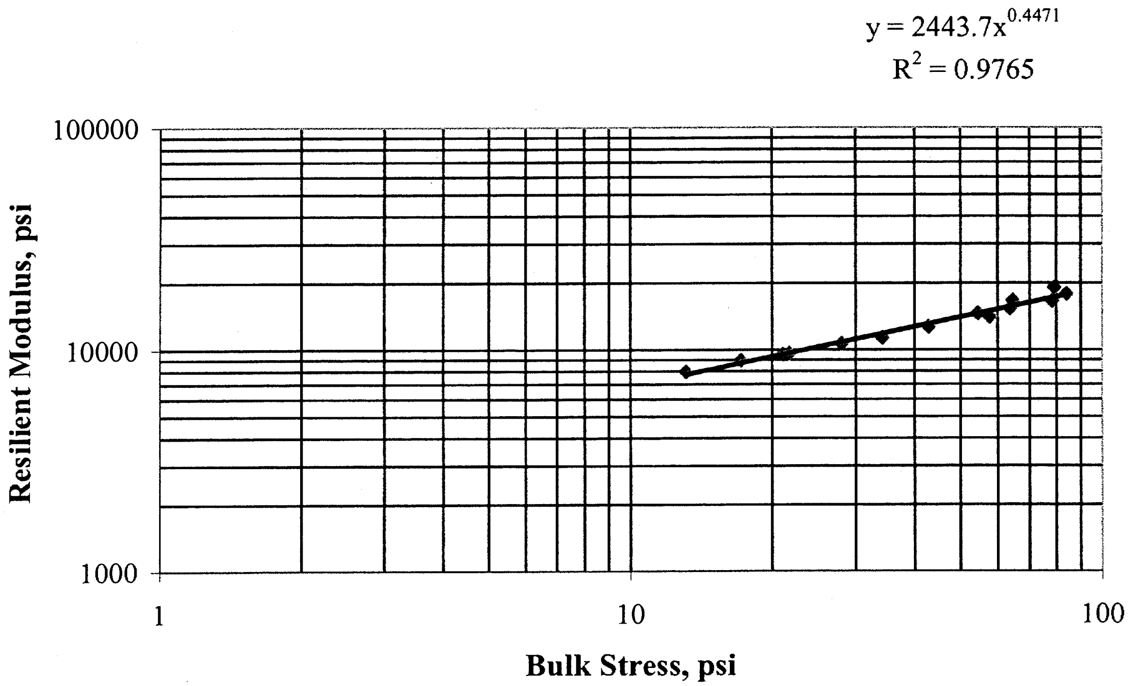


Figure 5.11a: Relationship between Resilient Modulus and Bulk Stress

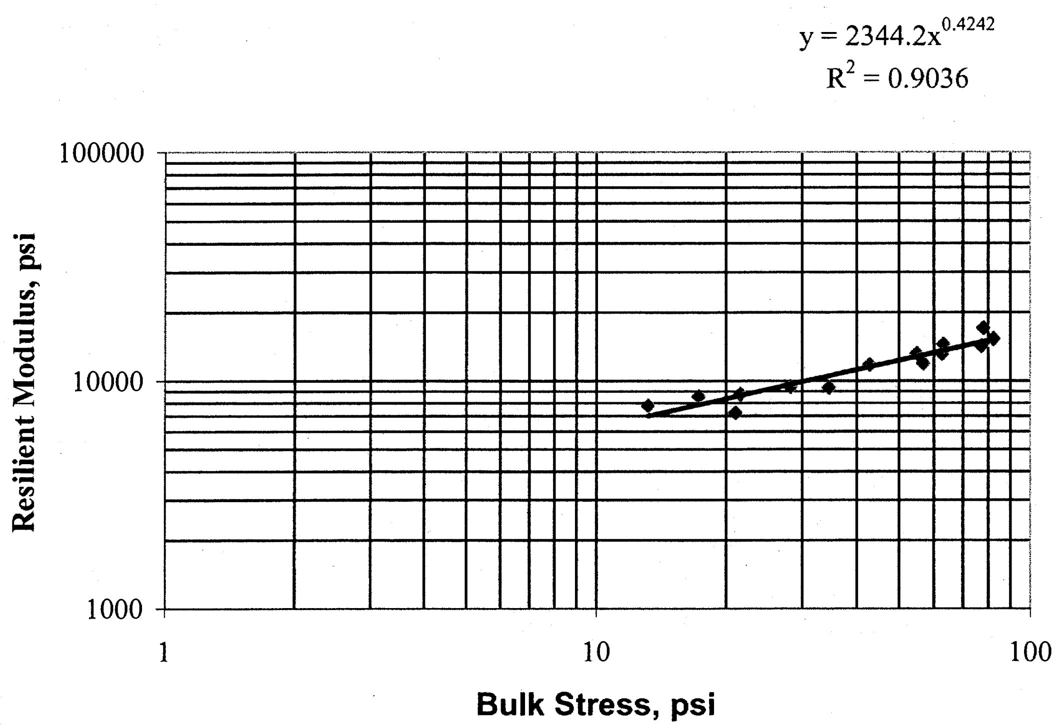


Figure 5.11b: Relationship between Resilient Modulus and Bulk Stress

Determination of Subgrade Resilient Modulus by Empirical Method

In Ohio soils are primarily classified based on the Atterburg's limits and gradation. After determining the gradation and Atterburg's limit of the soil, the following procedures is followed to determine the subgrade resilient modulus as mentioned in Roadway Design Manual of Ohio Department of Transportation [5].

- Determine the Group Index from Figure 701-2.
- Determination of California Bearing Ratio from Figure 701-3
- Calculate the resilient modulus based on equation in the Figure 701-3.

The subgrade soils in this project had the following gradation and Atterburg's limits

- 50% passing No. 200 sieve
- Liquid Limit = 22.8
- Plastic limit = 16.7
- Plasticity Index = 6.1

Determination of the resilient modulus values.

- Group Index = 4
- CBR value = 8
- Resilient Modulus = 1200 * CBR psi

= 1200 * 8 = **9600 psi.**

Laboratory Test Results

The laboratory test results on the subgrade showed a wide variation in the resilient modulus values because of the varying moisture content. The test conducted at a moisture content of 8.5% recorded lower average resilient modulus of 9 ksi when compared with the results from the test conducted at a 5.5 % moisture content that recorded 13 ksi as the average resilient modulus. This indicates that soils containing high clay content are very susceptible to the effect of moisture, resulting in lower resilient modulus values with high moisture content. As expected, the effect of the moisture content on the base was insignificant.

It is evident from Figures 5.11a and 5.11b for the bulk stress vs. resilient modulus that the resilient modulus values for untreated aggregate base depend on the stress state.

These graphs indicate a proportional increase in the resilient modulus values with the steady increase in bulk stress. An average resilient modulus of 10 ksi was recorded at a 5 psi confining pressure and an average resilient modulus value of 17 ksi was recorded at a confining pressure of 20 psi.

It should be noted that the resilient modulus values obtained from laboratory testing of the subgrade and base material are not equal to the elastic modulus values calculated from the deflection measurements obtained through various non-destructive testing methods. The resilient modulus values obtained from the laboratory results were less than the modulus values computed from various non-destructive testing devices. These variations in values arise from the difference in loading conditions between the field and the laboratory, as well as the differing boundary conditions for field and laboratory testing.

Chapter 6

Summary and Conclusions

Variability in subgrade and base layer stiffness can be a major cause of premature localized distress in pavement structures and often can be attributed to the nonuniformity of materials, subgrade moisture and construction practices. This investigation focused on the measurement of subgrade and base stiffness with the Falling Weight Deflectometer (FWD), the Humboldt Stiffness Gauge and the German Plate Load Test on an actual highway construction project to determine their effectiveness in evaluating the structural integrity of these layers.

In this study, base stiffness refers to a composite of the entire base layer and whatever depth of subgrade is required to support the applied test load and base modulus refers to the base layer alone. While this distinction is important when discussing stiffness and modulus determined with the FWD and German Plate Load Test, it is less significant with the Humboldt Stiffness Gauge, which only monitors the upper six inches of material. Tables 5.1, 5.2 and 5.3 summarize values for stiffness and modulus calculated with these devices at individual points along the test strip during construction of the subgrade and base. Despite the wide range of results, a few values were considered to be quite unrealistic. They were marked with an asterisk and omitted in the calculations of mean and variation.

The large variation within each data set makes it difficult to compare mean values when the three devices collected data at different locations; i.e., 1) because of a low battery, the Stiffness Gauge was not used on the subgrade beyond Station 425, and 2) because of the time required to conduct each test, the test interval used with the German Plate was 100 feet rather than the 50-foot interval used with the other devices. Therefore, adjusted means and variations were calculated for each data set using only those 15 locations on the subgrade and only those 16 locations on the base where valid data were available for all three devices and all test conditions. These values are shown in Table 6.1.

Table 6.1 –Stiffness and Modulus Adjusted for Common Stations

	Stiffness Gauge		Falling Weight Deflectometer				German Plate Test			
			Large Load		Small Load		First Cycle		Second Cycle	
	Stiffness Lb./in.	Modulus Ksi	Stiffness Lb./in.	Modulus Ksi	Stiffness Lb./in.	Modulus Ksi	Stiffness Lb./in.	Modulus Ksi	Stiffness Lb./in.	Modulus Ksi
Subgrade (15 stations)										
Mean	88,758	18.75	249,703	22.61	210,785	19.09	131,889	11.96	153,795	13.93
Variation	0.25	0.25	0.77	0.77	0.63	0.63	0.82	0.82	0.73	0.73
Composite Base (16 stations)										
Mean	129736	27.41	252,747	36.22	257,114	40.97	67,793	16.87	206533	44.50
Variation	0.23	0.23	0.55	0.64	0.67	0.84	0.49	1.45	0.55	0.67

The conclusions of this study, drawn from Table 6.1, are presented below:

1. Average Stiffness and Modulus

   a. Mean stiffness and modulus calculated on the subgrade with the first and second loading cycles of the German Plate Load Test appear to be quite reasonable, with values for the second cycle being about 17 % larger than for the first cycle. On the base, however, stiffness and modulus were more than 200% larger on the second loading cycle than on the first cycle. Considering the magnitude of this difference in stiffness between the first and second loading cycles on the base, the subgrade measuring twice as stiff as the base using data from the first loading cycle, and the consistent trend with the other devices of having a stiffer base than subgrade, it is concluded that the second loading cycle on the German Plate provided better estimates of base stiffness than did the first loading cycle. This may have been caused by the dense graded aggregate base surface being disturbed as it was leveled to improve contact with the load plate and some loose material being left on the surface. The second cycle measurement appeared to be more representative of the in-situ material. In view of the time required to set up the German Plate, it is recommended that two loading cycles routinely be recorded at each location and the results of the second cycle be adopted for the calculation of stiffness.

b. Average stiffness and modulus of the subgrade and base layers were highest when calculated with measurements from the FWD, followed by the German Plate Load Test (second loading cycle) and the Humboldt Stiffness Gauge.

c. There were only slight differences between average stiffness calculated on the subgrade and base layers with the small (3,500-4,500 lb.f) and large (6,500-9,000 lb.f) FWD loads. These trends suggest nearly equal stiffness and a nearly linear response for the subgrade and base layers to these loads.

d. With the exception of stiffness on the first load cycle on the German Plate Load Test, the stiffness and modulus of the base were larger than the stiffness and modulus of the subgrade using all three devices. This would be expected with a compacted dense graded aggregate base over a fine-grained clay subgrade.

2. Variations in Stiffness and Modulus

a. As shown in Tables 5.1, 5.2, 5.3 and 6.1, large variations were observed in base and subgrade stiffness and modulus at individual points along the length of the test section with the FWD and German Plate. Much smaller variations were noted with the Humboldt Stiffness Gauge. This is reasonable since the Humboldt only measures the stiffness of the upper six inches of material, which was closely controlled during construction with respect to material content and placement. Stiffness of the underlying support layers, largely unknown and likely nonuniform along the section length, is a factor in the FWD and German Plate measurements.

b. The Coefficients of Variation are equal for the stiffness and modulus on single-layer structures because of the direct correlation between the two parameters. This is also true for the Humboldt Stiffness Gauge on multilayer systems because of its limitation to measuring the upper six inches of material.

3. Laboratory Tests

   a. For subgrade material, resilient modulus determined in the laboratory were:

      - About the same as moduli determined on site with the German Plate Load Test
      - 26% lower than moduli determined on site with the Humboldt Stiffness Gauge
      - 42% lower than moduli determined on site with the FWD

   b. For base material, resilient modulus determined in the laboratory were:

      - 20% lower than moduli determined on site with the German Plate Load Test
      - 40% lower than moduli determined on site with the Humboldt Stiffness Gauge
      - 62% lower than moduli determined on site with the FWD

It is difficult to directly compare results of the FWD, German Plate Load Test and Humboldt Stiffness Gauge because they are measuring to different depths, they utilize different technologies to induce load and measure in-situ response, and different equations are used to convert surface deformation to layer modulus, particularly on two-layered pavement structures. Data obtained in this study indicate strongly that the devices do give similar magnitudes of stiffness and modulus, and similar trends in the data with regard to relative stiffness of the in-situ layers.

The types of response being measured with these devices include: dynamic response to heavy loads dropped on the surface with the FWD, static response generated as load is gradually increased during the German Plate Load Test, and dynamic response to small excitations generated by the Humboldt Stiffness Gauge which limits its depth of effectiveness. Dynamic loads typically reflect higher material stiffness than static loads, and the measurement of stiffness to a greater depth in a nonuniform pavement structure will certainly increase variability within the measurements.

The Humboldt Stiffness Gauge is an effective tool for monitoring the integrity of individual material lifts as they are constructed, since the measurements are limited to that lift. Conversely, the FWD and German Plate Load Test are effective in measuring the total composite stiffness of in-situ pavement structures. The FWD has a definite advantage over the German Plate Load Test in being faster, less labor intensive and able to provide much better coverage within a given period of time. If specific areas of the pavement are identified with the FWD as having unusually low stiffness, the Dynamic Cone Penetrometer can be used to identify the cause(s) of low stiffness and locate specific layers within the structure which will likely cause premature distress. Engineers can then assess the cost and benefits of correcting the problem early to extend the service life of the pavement, and avoid higher maintenance costs and public inconvenience later.

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APPENDIX A: Raw Data for German Plate Load Test

Table A.1:German Plate Load Test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
410+50	0.06	0.004	952	0.12	0.0047	07/06/1999
	0.1	0.007	1587	0.2	0.0079	
	0.16	0.011	2538	0.32	0.0126	Dry Surface
	0.2	0.014	3173	0.38	0.0150	
	0.25	0.018	3966	0.42	0.0165	
	0.29	0.020	4601	0.48	0.0189	
	0.19	0.013	3014	0.42	0.0165	
	0.09	0.006	1428	0.36	0.0142	
	0.05	0.004	793	0.24	0.0094	
	0.1	0.007	1587	0.3	0.0118	
	0.16	0.011	2538	0.36	0.0142	
	0.2	0.014	3173	0.44	0.0173	
	0.24	0.017	3808	0.46	0.0181	
	0.29	0.020	4601	0.52	0.0205	
411+50	0.06	0.004	952	0.12	0.0047	07/06/1999
	0.1	0.007	1587	0.18	0.0071	
	0.15	0.011	2380	0.24	0.0094	Dry Surface
	0.2	0.014	3173	0.28	0.0110	
	0.24	0.017	3808	0.32	0.0126	
	0.29	0.020	4601	0.38	0.0150	
	0.2	0.014	3173	0.34	0.0134	
	0.1	0.007	1587	0.28	0.0110	
	0.06	0.004	952	0.18	0.0071	
	0.1	0.007	1587	0.22	0.0087	
	0.15	0.011	2380	0.28	0.0110	
	0.19	0.013	3014	0.32	0.0126	
	0.25	0.018	3966	0.36	0.0142	
	0.29	0.020	4601	0.4	0.0157	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
412+50	0.050	0.004	793.258	0.240	0.009	07/06/1999
	0.100	0.007	1586.517	0.640	0.025	
	0.150	0.011	2379.775	1.100	0.043	Dry Surface
	0.200	0.014	3173.034	1.520	0.060	
	0.240	0.017	3807.640	2.100	0.083	
	0.290	0.020	4600.899	2.600	0.102	
	0.200	0.014	3173.034	2.520	0.099	
	0.100	0.007	1586.517	2.160	0.085	
	0.050	0.004	793.258	1.480	0.058	
	0.100	0.007	1586.517	1.680	0.066	
	0.140	0.010	2221.124	1.980	0.078	
	0.200	0.014	3173.034	2.180	0.086	
	0.250	0.018	3966.292	2.480	0.098	
	0.290	0.020	4600.899	2.720	0.107	
	0.280	0.020	4442.247	2.760	0.109	
413+50	0.050	0.004	793.258	0.140	0.006	07/06/1999
	0.100	0.007	1586.517	0.480	0.019	
	0.150	0.011	2379.775	0.900	0.035	Dry Surface
	0.200	0.014	3173.034	1.380	0.054	
	0.250	0.018	3966.292	1.660	0.065	
	0.300	0.021	4759.551	2.080	0.082	
	0.200	0.014	3173.034	2.040	0.080	
	0.100	0.007	1586.517	1.800	0.071	
	0.050	0.004	793.258	1.260	0.050	
	0.090	0.006	1427.865	1.440	0.057	
	0.160	0.011	2538.427	1.700	0.067	
	0.200	0.014	3173.034	1.840	0.072	
	0.250	0.018	3966.292	2.020	0.080	
	0.300	0.021	4759.551	2.240	0.088	

Table A.1:German Plate Load test Raw Data for Subgrade

Station No	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
414+50	0.07	0.005	1110.562	0.26	0.0102	07/06/1999
	0.1	0.007	1586.517	0.4	0.0157	
	0.16	0.011	2538.427	0.56	0.0220	Dry Surface
	0.21	0.015	3331.685	0.74	0.0291	
	0.26	0.018	4124.944	0.9	0.0354	
	0.29	0.020	4600.899	1.02	0.0402	
	0.2	0.014	3173.034	0.96	0.0378	
	0.18	0.013	2855.730	0.9	0.0354	
	0.1	0.007	1586.517	0.72	0.0283	
	0.06	0.004	951.910	0.34	0.0134	
	0.1	0.007	1586.517	0.48	0.0189	
	0.16	0.011	2538.427	0.66	0.0260	
	0.2	0.014	3173.034	0.8	0.0315	
	0.25	0.018	3966.292	0.94	0.0370	
	0.28	0.020	4442.247	1.04	0.0409	
415+50	0.06	0.004	951.910	0	0.0000	07/06/1999
	0.1	0.007	1586.517	0.02	0.0008	
	0.16	0.011	2538.427	0.1	0.0039	Dry Surface
	0.2	0.014	3173.034	0.2	0.0079	
	0.25	0.018	3966.292	0.3	0.0118	
	0.28	0.020	4442.247	0.4	0.0157	
	0.2	0.014	3173.034	0.34	0.0134	
	0.09	0.006	1427.865	0.3	0.0118	
	0.06	0.004	951.910	0.22	0.0087	
	0.1	0.007	1586.517	0.28	0.0110	
	0.15	0.011	2379.775	0.32	0.0126	
	0.2	0.014	3173.034	0.32	0.0126	
	0.26	0.018	4124.944	0.38	0.0150	
	0.28	0.020	4442.247	0.44	0.0173	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
416+50	0.06	0.004	951.910	0.38	0.0150	07/06/1999
	0.1	0.007	1586.517	1.02	0.0402	
	0.15	0.011	2379.775	1.96	0.0772	Dry Surface
	0.19	0.013	3014.382	2.84	0.1118	
	0.25	0.018	3966.292	4.42	0.1740	
	0.28	0.020	4442.247	5.04	0.1984	
	0.19	0.013	3014.382	4.68	0.1843	
	0.25	0.018	3966.292	4.4	0.1732	
	0.28	0.020	4442.247	5.04	0.1984	
	0.19	0.013	3014.382	4.68	0.1843	
	0.1	0.007	1586.517	4.4	0.1732	
	0.07	0.005	1110.562	3.28	0.1291	
	0.1	0.007	1586.517	3.72	0.1465	
	0.16	0.011	2538.427	4.26	0.1677	
	0.2	0.014	3173.034	4.68	0.1843	
	0.25	0.018	3966.292	5.16	0.2031	
	0.29	0.020	4600.899	5.68	0.2236	
417+50	0.06	0.004	951.910	0.1	0.0039	07/06/1999
	0.1	0.007	1586.517	0.18	0.0071	
	0.15	0.011	2379.775	0.24	0.0094	Dry Surface
	0.19	0.013	3014.382	0.32	0.0126	
	0.25	0.018	3966.292	0.4	0.0157	
	0.29	0.020	4600.899	0.46	0.0181	
	0.2	0.014	3173.034	0.44	0.0173	
	0.1	0.007	1586.517	0.34	0.0134	
	0.06	0.004	951.910	0.14	0.0055	
	0.1	0.007	1586.517	0.22	0.0087	
	0.16	0.011	2538.427	0.28	0.0110	
	0.19	0.013	3014.382	0.32	0.0126	
	0.25	0.018	3966.292	0.4	0.0157	
	0.29	0.020	4600.899	0.48	0.0189	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
418+50	0.06	0.004	951.910	0.2	0.008	07/06/1999
	0.1	0.007	1586.517	0.28	0.011	
	0.15	0.011	2379.775	0.4	0.016	Dry Surface
	0.2	0.014	3173.034	0.5	0.020	
	0.25	0.018	3966.292	0.68	0.027	
	0.3	0.021	4759.551	0.7	0.028	
	0.2	0.014	3173.034	0.66	0.026	
	0.1	0.007	1586.517	0.52	0.020	
	0.06	0.004	951.910	0.2	0.008	
	0.1	0.007	1586.517	0.28	0.011	
	0.15	0.011	2379.775	0.38	0.015	
	0.2	0.014	3173.034	0.48	0.019	
	0.25	0.018	3966.292	0.6	0.024	
	0.29	0.020	4600.899	0.7	0.028	
419+50	0.06	0.004	951.910	0.2	0.008	07/06/1999
	0.1	0.007	1586.517	0.32	0.013	
	0.15	0.011	2379.775	0.5	0.020	Dry Surface
	0.2	0.014	3173.034	0.68	0.027	
	0.25	0.018	3966.292	0.86	0.034	
	0.29	0.020	4600.899	0.98	0.039	
	0.2	0.014	3173.034	0.94	0.037	
	0.1	0.007	1586.517	0.74	0.029	
	0.06	0.004	951.910	0.3	0.012	
	0.1	0.007	1586.517	0.44	0.017	
	0.16	0.011	2538.427	0.72	0.028	
	0.19	0.013	3014.382	0.76	0.030	
	0.25	0.018	3966.292	0.92	0.036	
	0.29	0.020	4600.899	1.06	0.042	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
420+50	0.06	0.004	951.910	0.24	0.009	07/06/1999
	0.1	0.007	1586.517	0.3	0.012	
	0.16	0.011	2538.427	0.36	0.014	Dry Surface
	0.2	0.014	3173.034	0.44	0.017	
	0.25	0.018	3966.292	0.44	0.017	
	0.28	0.020	4442.247	0.48	0.019	
	0.2	0.014	3173.034	0.46	0.018	
	0.1	0.007	1586.517	0.4	0.016	
	0.05	0.004	793.258	0.24	0.009	
	0.1	0.007	1586.517	0.32	0.013	
	0.16	0.011	2538.427	0.38	0.015	
	0.2	0.014	3173.034	0.42	0.017	
	0.26	0.018	4124.944	0.46	0.018	
	0.28	0.020	4442.247	0.5	0.020	
421+50	0.05	0.004	793.258	0	0.000	07/07/1999
	0.1	0.007	1586.517	0	0.000	
	0.15	0.011	2379.775	0.2	0.008	Wet Surface
	0.2	0.014	3173.034	0.42	0.017	
	0.24	0.017	3807.640	0.9	0.035	
	0.29	0.020	4600.899	1.44	0.057	
	0.19	0.013	3014.382	1.34	0.053	
	0.1	0.007	1586.517	0.96	0.038	
	0.05	0.004	793.258	0.18	0.007	
	0.1	0.007	1586.517	0.32	0.013	
	0.15	0.011	2379.775	0.62	0.024	
	0.19	0.013	3014.382	0.9	0.035	
	0.24	0.017	3807.640	1.22	0.048	
	0.29	0.020	4600.899	1.58	0.062	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
422+50	0.05	0.004	793.258	0.7	0.028	07/07/1999
	0.09	0.006	1427.865	2.44	0.096	
	0.15	0.011	2379.775	4.5	0.177	Wet Surface
	0.2	0.014	3173.034	7.74	0.305	
	0.24	0.017	3807.640	8.34	0.328	
	0.29	0.020	4600.899	9.96	0.392	
	0.2	0.014	3173.034	10.1	0.398	
	0.1	0.007	1586.517	9.14	0.360	
	0.05	0.004	793.258	6.4	0.252	
	0.1	0.007	1586.517	7.18	0.283	
	0.15	0.011	2379.775	8.16	0.321	
	0.2	0.014	3173.034	9.04	0.356	
	0.24	0.017	3807.640	10.02	0.394	
	0.29	0.020	4600.899	11.08	0.436	
423+50	0.05	0.004	793.258	0.36	0.014	07/07/1999
	0.1	0.007	1586.517	1.26	0.050	
	0.15	0.011	2379.775	2.48	0.098	Wet Surface
	0.2	0.014	3173.034	4.18	0.165	
	0.24	0.017	3807.640	4.86	0.191	
	0.29	0.020	4600.899	5.88	0.231	
	0.19	0.013	3014.382	5.66	0.223	
	0.1	0.007	1586.517	5.08	0.200	
	0.06	0.004	951.910	3.64	0.143	
	0.1	0.007	1586.517	4.3	0.169	
	0.15	0.011	2379.775	4.5	0.177	
	0.2	0.014	3173.034	4.96	0.195	
	0.24	0.017	3807.640	5.46	0.215	
	0.29	0.020	4600.899	6.08	0.239	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
424+50	0.05	0.004	793.258	0	0	07/07/1999
	0.1	0.007	1586.517	0.62	0.024	
	0.15	0.011	2379.775	3.34	0.131	Wet Surface
	0.2	0.014	3173.034	5.46	0.215	
	0.24	0.017	3807.640	8.08	0.318	
	0.29	0.020	4600.899	10.26	0.404	
	0.2	0.014	3173.034	10.04	0.395	
	0.11	0.008	1745.169	9.06	0.357	
	0.05	0.004	793.258	6.08	0.239	
	0.1	0.007	1586.517	6.86	0.270	
	0.15	0.011	2379.775	8	0.315	
	0.2	0.014	3173.034	8.78	0.346	
	0.25	0.018	3966.292	9.72	0.383	
	0.28	0.020	4442.247	10.84	0.427	
425+50	0.05	0.004	793.258	0	0.000	07/07/1999
	0.1	0.007	1586.517	0	0.000	
	0.15	0.011	2379.775	0.26	0.010	Wet Surface
	0.2	0.014	3173.034	0.7	0.028	
	0.25	0.018	3966.292	1.24	0.049	
	0.29	0.020	4600.899	1.76	0.069	
	0.2	0.014	3173.034	1.66	0.065	
	0.1	0.007	1586.517	1.4	0.055	
	0.06	0.004	951.910	0.86	0.034	
	0.1	0.007	1586.517	1	0.039	
	0.15	0.011	2379.775	1.22	0.048	
	0.2	0.014	3173.034	1.42	0.056	
	0.25	0.018	3966.292	1.64	0.065	
	0.29	0.020	4600.899	1.9	0.075	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
426+50	0.05	0.004	793.258	0.4	0.0157	07/07/1999
	0.1	0.007	1586.517	0.82	0.0323	
	0.15	0.011	2379.775	1.42	0.0559	Wet Surface
	0.2	0.014	3173.034	1.82	0.0717	
	0.25	0.018	3966.292	2.32	0.0913	
	0.3	0.021	4759.551	2.94	0.1157	
	0.2	0.014	3173.034	2.76	0.1087	
	0.1	0.007	1586.517	2.4	0.0945	
	0.05	0.004	793.258	1.72	0.0677	
	0.1	0.007	1586.517	1.92	0.0756	
	0.15	0.011	2379.775	2.2	0.0866	
	0.2	0.014	3173.034	2.36	0.0929	
	0.25	0.018	3966.292	2.68	0.1055	
	0.3	0.021	4759.551	2.98	0.1173	
427+50	0.05	0.004	793.258	1.36	0.0535	07/07/1999
	0.1	0.007	1586.517	3.42	0.1346	
	0.15	0.011	2379.775	5.64	0.2220	Wet Surface
	0.2	0.014	3173.034	7.26	0.2858	
	0.25	0.018	3966.292	9.48	0.3732	
	0.3	0.021	4759.551	11.38	0.4480	
	0.2	0.014	3173.034	11.06	0.4354	
	0.1	0.007	1586.517	9.76	0.3843	
	0.05	0.004	793.258	8.08	0.3181	
	0.1	0.007	1586.517	8.7	0.3425	
	0.15	0.011	2379.775	9.6	0.3780	
	0.19	0.013	3014.382	10.12	0.3984	
	0.25	0.018	3966.292	10.94	0.4307	
	0.3	0.021	4759.551	12.04	0.4740	

Table A.1:German Plate Load test Raw Data for Subgrade

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
428+50	0.05	0.004	793.258	0.96	0.038	07/07/1999
	0.1	0.007	1586.517	2.68	0.106	
	0.15	0.011	2379.775	4.98	0.196	Wet Surface
	0.2	0.014	3173.034	7.14	0.281	
	0.25	0.018	3966.292	8.46	0.333	
	0.3	0.021	4759.551	8.48	0.334	
	0.2	0.014	3173.034	8.48	0.334	
	0.1	0.007	1586.517	5.96	0.235	
	0.05	0.004	793.258	6.78	0.267	
	0.1	0.007	1586.517	7.76	0.306	
	0.15	0.011	2379.775	8.44	0.332	
	0.2	0.014	3173.034	8.48	0.334	
	0.25	0.018	3966.292	8.48	0.334	
	0.3	0.021	4759.551	8.52	0.335	
429+50	0.06	0.004	951.910	0.14	0.006	07/07/1999
	0.1	0.007	1586.517	0.18	0.007	
	0.15	0.011	2379.775	0.18	0.007	Wet Surface
	0.2	0.014	3173.034	0.18	0.007	
	0.25	0.018	3966.292	0.18	0.007	
	0.29	0.020	4600.899	0.24	0.009	
	0.2	0.014	3173.034	0.22	0.009	
	0.1	0.007	1586.517	0.18	0.007	
	0.05	0.004	793.258	0.18	0.007	
	0.1	0.007	1586.517	0.18	0.007	
	0.15	0.011	2379.775	0.18	0.007	
	0.2	0.014	3173.034	0.18	0.007	
	0.24	0.017	3807.640	0.18	0.007	
	0.29	0.020	4600.899	0.24	0.009	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
410+50	0.05	0.004	793.258	0.14	0.006	08/04/1999
	0.1	0.007	1586.517	0.26	0.010	
	0.15	0.011	2379.775	0.56	0.022	
	0.2	0.014	3173.034	1.34	0.053	
	0.25	0.018	3966.292	1.44	0.057	
	0.29	0.020	4600.899	1.62	0.064	
	0.19	0.013	3014.382	1.56	0.061	
	0.1	0.007	1586.517	1.48	0.058	
	0.05	0.004	793.258	1.38	0.054	
	0.09	0.006	1427.865	1.46	0.057	
	0.15	0.011	2379.775	1.56	0.061	
	0.19	0.013	3014.382	1.58	0.062	
	0.24	0.017	3807.640	1.64	0.065	
	0.28	0.020	4442.247	1.76	0.069	
411+50	0.05	0.004	793.258	0.48	0.019	08/04/1999
	0.09	0.006	1427.865	0.88	0.035	
	0.14	0.010	2221.124	1.22	0.048	
	0.19	0.013	3014.382	1.42	0.056	
	0.24	0.017	3807.640	1.6	0.063	
	0.29	0.020	4600.899	1.8	0.071	
	0.2	0.014	3173.034	1.78	0.070	
	0.1	0.007	1586.517	1.7	0.067	
	0.05	0.004	793.258	1.54	0.061	
	0.09	0.006	1427.865	1.6	0.063	
	0.14	0.010	2221.124	1.66	0.065	
	0.19	0.013	3014.382	1.72	0.068	
	0.24	0.017	3807.640	1.78	0.070	
	0.29	0.020	4600.899	1.88	0.074	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
412+50	0.05	0.004	793.258	0.2	0.008	08/04/1999
	0.1	0.007	1586.517	0.38	0.015	
	0.15	0.011	2379.775	0.62	0.024	
	0.19	0.013	3014.382	0.82	0.032	
	0.24	0.017	3807.640	1.02	0.040	
	0.29	0.020	4600.899	1.24	0.049	
	0.21	0.015	3331.685	1.22	0.048	
	0.11	0.008	1745.169	1.06	0.042	
	0.06	0.004	951.910	0.76	0.030	
	0.1	0.007	1586.517	0.86	0.034	
	0.15	0.011	2379.775	0.98	0.039	
	0.2	0.014	3173.034	1.12	0.044	
	0.25	0.018	3966.292	1.24	0.049	
	0.29	0.020	4600.899	1.36	0.054	
413+50	0.05	0.004	793.258	0.1	0.004	08/04/1999
	0.09	0.006	1427.865	0.28	0.011	
	0.14	0.010	2221.124	0.4	0.016	
	0.19	0.013	3014.382	0.5	0.020	
	0.24	0.017	3807.640	0.62	0.024	
	0.29	0.020	4600.899	0.76	0.030	
	0.2	0.014	3173.034	0.76	0.030	
	0.1	0.007	1586.517	0.66	0.026	
	0.05	0.004	793.258	0.5	0.020	
	0.1	0.007	1586.517	0.56	0.022	
	0.15	0.011	2379.775	0.62	0.024	
	0.19	0.013	3014.382	0.68	0.027	
	0.24	0.017	3807.640	0.74	0.029	
	0.29	0.020	4600.899	0.8	0.031	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
414+50	0.06	0.004	951.910	0.64	0.025	08/04/1999
	0.1	0.007	1586.517	1.02	0.040	
	0.15	0.011	2379.775	1.42	0.056	
	0.21	0.015	3331.685	1.82	0.072	
	0.26	0.018	4124.944	2.12	0.083	
	0.31	0.022	4918.202	2.4	0.094	
	0.22	0.016	3490.337	2.4	0.094	
	0.12	0.008	1903.820	2.3	0.091	
	0.07	0.005	1110.562	2.12	0.083	
	0.11	0.008	1745.169	2.18	0.086	
	0.16	0.011	2538.427	2.26	0.089	
	0.21	0.015	3331.685	2.34	0.092	
	0.26	0.018	4124.944	2.4	0.094	
	0.31	0.022	4918.202	2.54	0.100	
415+50	0.05	0.004	793.258	0.6	0.024	08/04/1999
	0.1	0.007	1586.517	1.4	0.055	
	0.15	0.011	2379.775	1.74	0.069	
	0.2	0.014	3173.034	2.1	0.083	
	0.26	0.018	4124.944	2.32	0.091	
	0.31	0.022	4918.202	2.54	0.100	
	0.21	0.015	3331.685	2.54	0.100	
	0.11	0.008	1745.169	2.46	0.097	
	0.05	0.004	793.258	2.36	0.093	
	0.1	0.007	1586.517	2.4	0.094	
	0.15	0.011	2379.775	2.44	0.096	
	0.2	0.014	3173.034	2.48	0.098	
	0.26	0.018	4124.944	2.52	0.099	
	0.3	0.021	4759.551	2.56	0.101	
	0.31	0.022	4918.202	2.58	0.102	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
416+50	0.05	0.004	793.258	0.16	0.006	08/04/1999
	0.09	0.006	1427.865	0.4	0.016	
	0.14	0.010	2221.124	0.64	0.025	
	0.19	0.013	3014.382	0.88	0.035	
	0.24	0.017	3807.640	1.1	0.043	
	0.28	0.020	4442.247	1.28	0.050	
	0.2	0.014	3173.034	1.32	0.052	
	0.1	0.007	1586.517	1.12	0.044	
	0.05	0.004	793.258	1	0.039	
	0.1	0.007	1586.517	1.08	0.043	
	0.15	0.011	2379.775	1.14	0.045	
	0.19	0.013	3014.382	1.22	0.048	
	0.25	0.018	3966.292	1.3	0.051	
	0.28	0.020	4442.247	1.4	0.055	
417+50	0.05	0.004	793.258	0.46	0.018	08/04/1999
	0.1	0.007	1586.517	0.76	0.030	
	0.14	0.010	2221.124	0.98	0.039	
	0.2	0.014	3173.034	1.14	0.045	
	0.24	0.017	3807.640	1.36	0.054	
	0.29	0.020	4600.899	1.5	0.059	
	0.19	0.013	3014.382	1.48	0.058	
	0.1	0.007	1586.517	1.4	0.055	
	0.05	0.004	793.258	1.26	0.050	
	0.1	0.007	1586.517	1.32	0.052	
	0.15	0.011	2379.775	1.38	0.054	
	0.19	0.013	3014.382	1.44	0.057	
	0.24	0.017	3807.640	1.48	0.058	
	0.29	0.020	4600.899	1.56	0.061	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
418+50	0.05	0.004	793.258	0.38	0.0150	08/04/1999
	0.1	0.007	1586.517	0.6	0.0236	
	0.14	0.010	2221.124	0.8	0.0315	
	0.19	0.013	3014.382	0.96	0.0378	
	0.24	0.017	3807.640	1.12	0.0441	
	0.29	0.020	4600.899	1.26	0.0496	
	0.19	0.013	3014.382	1.26	0.0496	
	0.1	0.007	1586.517	1.18	0.0465	
	0.05	0.004	793.258	1.02	0.0402	
	0.1	0.007	1586.517	1.08	0.0425	
	0.15	0.011	2379.775	1.14	0.0449	
	0.19	0.013	3014.382	1.18	0.0465	
	0.24	0.017	3807.640	1.24	0.0488	
419+50	0.05	0.004	793.258	0.54	0.0213	08/04/1999
	0.1	0.007	1586.517	0.98	0.0386	
	0.15	0.011	2379.775	1.26	0.0496	
	0.19	0.013	3014.382	1.5	0.0591	
	0.24	0.017	3807.640	1.68	0.0661	
	0.29	0.020	4600.899	1.82	0.0717	
	0.2	0.014	3173.034	1.82	0.0717	
	0.1	0.007	1586.517	1.74	0.0685	
	0.06	0.004	951.910	1.62	0.0638	
	0.1	0.007	1586.517	1.68	0.0661	
	0.15	0.011	2379.775	1.72	0.0677	
	0.2	0.014	3173.034	1.78	0.0701	
	0.24	0.017	3807.640	1.84	0.0724	
	0.29	0.020	4600.899	1.89	0.0744	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
420+50	0.05	0.004	793.258	0.36	0.014	08/04/1999
	0.1	0.007	1586.517	0.62	0.024	
	0.15	0.011	2379.775	0.82	0.032	
	0.19	0.013	3014.382	1.02	0.040	
	0.24	0.017	3807.640	1.14	0.045	
	0.29	0.020	4600.899	1.3	0.051	
	0.19	0.013	3014.382	1.3	0.051	
	0.1	0.007	1586.517	1.24	0.049	
	0.05	0.004	793.258	1.06	0.042	
	0.1	0.007	1586.517	1.14	0.045	
	0.15	0.011	2379.775	1.2	0.047	
	0.19	0.013	3014.382	1.24	0.049	
	0.24	0.017	3807.640	1.3	0.051	
	0.29	0.020	4600.899	1.38	0.054	
421+50	0.05	0.004	793.258	0.36	0.014	08/04/1999
	0.1	0.007	1586.517	0.88	0.035	
	0.15	0.011	2379.775	1.44	0.057	
	0.2	0.014	3173.034	2.06	0.081	
	0.25	0.018	3966.292	2.66	0.105	
	0.3	0.021	4759.551	3.62	0.143	
	0.21	0.015	3331.685	3.5	0.138	
	0.11	0.008	1745.169	3.08	0.121	
	0.05	0.004	793.258	2.12	0.083	
	0.1	0.007	1586.517	2.4	0.094	
	0.15	0.011	2379.775	2.7	0.106	
	0.2	0.014	3173.034	2.96	0.117	
	0.25	0.018	3966.292	3.3	0.130	
	0.3	0.021	4759.551	3.62	0.143	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
422+50	0.05	0.004	793.258	0.46	0.018	08/04/1999
	0.1	0.007	1586.517	0.92	0.036	
	0.14	0.010	2221.124	1.46	0.057	
	0.19	0.013	3014.382	1.92	0.076	
	0.24	0.017	3807.640	2.6	0.102	
	0.29	0.020	4600.899	3.16	0.124	
	0.2	0.014	3173.034	3.06	0.120	
	0.1	0.007	1586.517	2.74	0.108	
	0.05	0.004	793.258	1.98	0.078	
	0.1	0.007	1586.517	2.22	0.087	
	0.15	0.011	2379.775	2.48	0.098	
	0.19	0.013	3014.382	2.72	0.107	
	0.24	0.017	3807.640	2.96	0.117	
	0.29	0.020	4600.899	3.26	0.128	
423+50	0.05	0.004	793.258	0.32	0.013	08/04/1999
	0.1	0.007	1586.517	0.74	0.029	
	0.14	0.010	2221.124	1.18	0.046	
	0.19	0.013	3014.382	1.68	0.066	
	0.24	0.017	3807.640	2.24	0.088	
	0.28	0.020	4442.247	2.82	0.111	
	0.2	0.014	3173.034	2.66	0.105	
	0.11	0.008	1745.169	2.36	0.093	
	0.05	0.004	793.258	1.6	0.063	
	0.1	0.007	1586.517	1.88	0.074	
	0.15	0.011	2379.775	2.12	0.083	
	0.2	0.014	3173.034	2.38	0.094	
	0.24	0.017	3807.640	2.64	0.104	
	0.29	0.020	4600.899	2.94	0.116	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
424+50	0.05	0.004	793.258	0.52	0.020	08/04/1999
	0.09	0.006	1427.865	1.22	0.048	
	0.14	0.010	2221.124	2	0.079	
	0.19	0.013	3014.382	2.92	0.115	
	0.24	0.017	3807.640	3.96	0.156	
	0.28	0.020	4442.247	4.98	0.196	
	0.2	0.014	3173.034	4.78	0.188	
	0.11	0.008	1745.169	4.28	0.169	
	0.05	0.004	793.258	2.94	0.116	
	0.1	0.007	1586.517	3.36	0.132	
	0.15	0.011	2379.775	3.8	0.150	
	0.2	0.014	3173.034	4.24	0.167	
	0.25	0.018	3966.292	4.68	0.184	
	0.3	0.021	4759.551	5.26	0.207	
425+50	0.06	0.004	951.910	0.2	0.008	08/04/1999
	0.1	0.007	1586.517	0.4	0.016	
	0.15	0.011	2379.775	0.66	0.026	
	0.2	0.014	3173.034	0.96	0.038	
	0.25	0.018	3966.292	1.28	0.050	
	0.3	0.021	4759.551	1.64	0.065	
	0.21	0.015	3331.685	1.56	0.061	
	0.11	0.008	1745.169	1.4	0.055	
	0.06	0.004	951.910	1.04	0.041	
	0.11	0.008	1745.169	1.16	0.046	
	0.16	0.011	2538.427	1.3	0.051	
	0.21	0.015	3331.685	1.4	0.055	
	0.25	0.018	3966.292	1.56	0.061	
	0.3	0.021	4759.551	1.72	0.068	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
426+50	0.06	0.004	951.910	0.3	0.012	08/04/1999
	0.11	0.008	1745.169	0.48	0.019	
	0.16	0.011	2538.427	0.72	0.028	
	0.21	0.015	3331.685	0.94	0.037	
	0.26	0.018	4124.944	1.16	0.046	
	0.31	0.022	4918.202	1.36	0.054	
	0.22	0.016	3490.337	1.34	0.053	
	0.11	0.008	1745.169	1.24	0.049	
	0.06	0.004	951.910	1.04	0.041	
	0.11	0.008	1745.169	1.16	0.046	
	0.16	0.011	2538.427	1.22	0.048	
	0.21	0.015	3331.685	1.3	0.051	
	0.26	0.018	4124.944	1.38	0.054	
	0.32	0.023	5076.854	1.48	0.058	
427+50	0.05	0.004	793.258	0.44	0.017	08/04/1999
	0.1	0.007	1586.517	0.69	0.027	
	0.15	0.011	2379.775	1.5	0.059	
	0.2	0.014	3173.034	1.96	0.077	
	0.24	0.017	3807.640	2.46	0.097	
	0.29	0.020	4600.899	2.98	0.117	
	0.2	0.014	3173.034	2.62	0.103	
	0.11	0.008	1745.169	2.52	0.099	
	0.05	0.004	793.258	1.98	0.078	
	0.1	0.007	1586.517	2.16	0.085	
	0.15	0.011	2379.775	2.4	0.094	
	0.2	0.014	3173.034	2.56	0.101	
	0.24	0.017	3807.640	2.82	0.111	
	0.29	0.020	4600.899	3.08	0.121	

Table A.2:German Plate Load test Raw Data for Base

Station	Normal Stress (MN/m^2)	Load (MN)	Load (lb)	Settlement (mm)	Settlement (in)	Remarks
428+50	0.05	0.004	793.258	0.6	0.024	08/04/1999
	0.1	0.007	1586.517	1.14	0.045	
	0.15	0.011	2379.775	1.68	0.066	
	0.21	0.015	3331.685	2.3	0.091	
	0.26	0.018	4124.944	2.9	0.114	
	0.31	0.022	4918.202	3.32	0.131	
	0.22	0.016	3490.337	3.32	0.131	
	0.11	0.008	1745.169	3.04	0.120	
	0.06	0.004	951.910	2.42	0.095	
	0.11	0.008	1745.169	2.62	0.103	
	0.16	0.011	2538.427	2.86	0.113	
	0.21	0.015	3331.685	3.02	0.119	
	0.26	0.018	4124.944	3.24	0.128	
	0.31	0.022	4918.202	3.5	0.138	
429+50	0.05	0.004	793.258	0.26	0.010	08/04/1999
	0.1	0.007	1586.517	1.06	0.042	
	0.14	0.010	2221.124	1.84	0.072	
	0.19	0.013	3014.382	2.74	0.108	
	0.24	0.017	3807.640	3.66	0.144	
	0.29	0.020	4600.899	4.6	0.181	
	0.2	0.014	3173.034	4.48	0.176	
	0.11	0.008	1745.169	4.08	0.161	
	0.05	0.004	793.258	3.04	0.120	
	0.1	0.007	1586.517	3.38	0.133	
	0.15	0.011	2379.775	3.74	0.147	
	0.2	0.014	3173.034	4.12	0.162	
	0.24	0.017	3807.640	4.52	0.178	
	0.3	0.021	4759.551	5	0.197	

APPENDIX B: Method of Equivalent Thickness for the Calculation of GPLT Base Moduli (First and Second Sequence)

Appendix B.1: Method of Equivalent thickness for the Calculation of GPLT Base(First Cycle)

Station No	Base E2 (psi)	Subgrade E3 (psi)	H2 (in)	He (in)	Fb	q (small) psi	R	v	Deflection (10^{-3} in)	Deflection at site (10^{-3} in)
410.5	1000.0	22048.3	6.0	2.1	0.9	42.1	5.9	0.4	58.7	63.8
411.5	500.0	27850.5	6.0	1.6	0.9	42.1	5.9	0.4	69.6	70.9
412.5	40000.0	4070.5	6.0	12.9	0.4	42.1	5.9	0.4	45.9	48.8
413.5	90000.0	5263.5	6.0	15.5	0.3	42.1	5.9	0.4	29.2	29.9
414.5	1000.0	10375.7	6.0	2.8	0.9	42.1	5.9	0.4	92.5	94.5
415.5	250.0	25545.6	6.0	1.3	0.9	42.1	5.9	0.4	101.3	100.0
416.5	105000.0	2027.4	6.0	22.4	0.2	42.1	5.9	0.4	51.4	50.4
417.5	1000.0	23006.9	6.0	2.1	0.9	42.1	5.9	0.4	57.2	59.1
418.5	2500.0	15640.2	6.0	3.3	0.8	42.1	5.9	0.4	50.8	49.6
419.5	2000.0	10799.2	6.0	3.4	0.8	42.1	5.9	0.4	69.8	71.7
420.5	1500.0	21288.0	6.0	2.5	0.9	42.1	5.9	0.4	50.9	51.2
421.5	650.0	7349.4	6.0	2.7	0.9	42.1	5.9	0.4	135.0	142.5
422.5	30000.0	1062.6	6.0	18.3	0.3	42.1	5.9	0.4	121.2	124.4
423.5	15000.0	1799.9	6.0	12.2	0.4	42.1	5.9	0.4	110.1	111.0
424.5	8000.0	1031.5	6.0	11.9	0.4	42.1	5.9	0.4	197.1	196.1
425.5	6500.0	6013.2	6.0	6.2	0.6	42.1	5.9	0.4	67.7	64.6
426.5	32000.0	3723.8	6.0	12.3	0.4	42.1	5.9	0.4	52.7	53.5
427.5	40000.0	962.0	6.0	20.8	0.3	42.1	5.9	0.4	116.9	117.3
428.5	18000.0	1291.1	6.0	14.4	0.3	42.1	5.9	0.4	127.9	130.7
429.5	55.0	44096.6	6.0	0.6	1.0	42.1	5.9	0.4	177.6	181.1

Appendix B.2: Method of Equivalent thickness for the Calculation of GPLT Base(Second Sequence)

Station No	Base E2 (psi)	Subgrade E3 (psi)	H2 (in)	He (in)	Fb	q (small) psi	R	v	Deflection (10^{-3} in)	Deflection at site (10^{-3} in)
410.5	20000.0	26452.8	6.0	5.5	0.7	42.1	5.9	0.4	17.4	18.1
411.5	25000.0	29392.0	6.0	5.7	0.7	42.1	5.9	0.4	15.0	16.5
412.5	55000.0	6811.8	6.0	12.0	0.4	42.1	5.9	0.4	29.4	28.3
413.5	130000.0	10136.0	6.0	14.0	0.4	42.1	5.9	0.4	16.8	15.7
414.5	50000.0	12163.9	6.0	9.6	0.5	42.1	5.9	0.4	20.9	21.3
415.5	60000.0	26888.6	6.0	7.8	0.6	42.1	5.9	0.4	11.7	11.0
416.5	225000.0	3861.7	6.0	23.3	0.2	42.1	5.9	0.4	25.9	20.5
417.5	30000.0	27845.0	6.0	6.2	0.6	42.1	5.9	0.4	14.6	15.7
418.5	60000.0	17635.2	6.0	9.0	0.5	42.1	5.9	0.4	15.4	14.2
419.5	185000.0	11756.8	6.0	15.0	0.3	42.1	5.9	0.4	13.5	12.6
420.5	55000.0	21286.8	6.0	8.2	0.5	42.1	5.9	0.4	14.1	15.7
421.5	5000.0	6961.3	6.0	5.4	0.7	42.1	5.9	0.4	67.3	68.5
422.5	60000.0	2099.4	6.0	18.3	0.3	42.1	5.9	0.4	61.1	59.0
423.5	20000.0	3725.7	6.0	10.5	0.5	42.1	5.9	0.4	62.2	61.4
424.5	15000.0	1899.2	6.0	11.9	0.4	42.1	5.9	0.4	106.4	104.7
425.5	30000.0	8397.7	6.0	9.2	0.5	42.1	5.9	0.4	31.9	32.3
426.5	32000.0	7108.3	6.0	9.9	0.5	42.1	5.9	0.4	34.7	20.5
427.5	65000.0	2750.5	6.0	17.2	0.3	42.1	5.9	0.4	49.9	49.0
428.5	30000.0	4276.1	6.0	11.5	0.4	42.1	5.9	0.4	49.3	50.0
429.5	150.0	176351.8	6.0	0.6	1.0	42.1	5.9	0.4	55.5	87.0

APPENDIX C: Method of Equivalent Thickness for the Calculation of FWD Base Moduli

Appendix C : Method of Equivalent thickness for the Calculation of FWD Base

Small Load											
Station No	Base E2 (psi)	Subgrade E3 (psi)	H2 (in)	He (in)	Fb	P (Small) (lb)	q (Small) (psi)	R	v	Deflection (10^{-3} in)	Deflection at site (10^{-3} in)
410.0	14000	105746	6.0	3.1	0.84	4639	42.3	5.91	0.4	8.09	8.06
410.5	16000	40348	6.0	4.4	0.75	3925	35.8	5.91	0.4	12.13	12.28
411.0	11000	84504	6.0	3.0	0.84	4396	40.1	5.91	0.4	9.66	9.64
411.5	8000	27061	6.0	4.0	0.78	3860	35.2	5.91	0.4	19.71	19.24
412.0	6000	63392	6.0	2.7	0.86	3953	36.0	5.91	0.4	13.05	13.49
412.5	30000	9167	6.0	8.9	0.51	3822	34.8	5.91	0.4	24.91	24.12
413.0	22000	14989	6.0	6.8	0.61	3756	34.2	5.91	0.4	19.84	19.71
413.5	35000	14651	6.0	8.0	0.55	2638	24.0	5.91	0.4	12.02	11.54
414.0	250000	7735	6.0	19.1	0.27	4084	37.2	5.91	0.4	14.04	13.16
414.5	22000	16630	6.0	6.6	0.62	3486	31.8	5.91	0.4	17.21	16.78
415.0	22000	42192	6.0	4.8	0.72	3392	30.9	5.91	0.4	9.11	8.84
415.5	60000	34661	6.0	7.2	0.59	3253	29.6	5.91	0.4	7.02	6.53
416.0	35000	101062	6.0	4.2	0.76	4101	37.4	5.91	0.4	5.30	4.89
416.5	450000	5996	6.0	25.3	0.21	4101	37.4	5.91	0.4	13.57	5.63
417.0	40000	65446	6.0	5.1	0.71	3942	35.9	5.91	0.4	6.46	5.88
417.5	135000	31650	6.0	9.7	0.48	4560	41.6	5.91	0.4	7.84	7.13
418.0	95000	48421	6.0	7.5	0.57	4117	37.5	5.91	0.4	6.08	7.16
418.5	32000	27162	6.0	6.3	0.63	3863	35.2	5.91	0.4	12.16	11.68
419.0	65000	9515	6.0	11.4	0.42	3625	33.0	5.91	0.4	17.54	17.6
419.5	55000	20393	6.0	8.4	0.53	4245	38.7	5.91	0.4	13.32	12.69

Appendix C : Method of Equivalent thickness for the Calculation of FWD Base

420.0	550000	6817	6.0	25.9	0.20	4245	38.7	5.91	0.4	12.05	10.71
420.5	95000	30005	6.0	8.8	0.51	3950	36.0	5.91	0.4	7.96	7.29
421.0	90000	7857	6.0	13.5	0.37	3769	34.3	5.91	0.4	18.39	18.27
421.5	10000	12140	6.0	5.6	0.68	3592	32.7	5.91	0.4	28.63	29.31
422.0	55000	5342	6.0	13.1	0.38	3737	34.1	5.91	0.4	27.85	27.45
422.5	50000	5402	6.0	12.6	0.39	3535	32.2	5.91	0.4	27.05	27.44
423.0	100000	10341	6.0	12.8	0.39	4043	36.8	5.91	0.4	15.91	16.48
423.5	13000	7067	6.0	7.4	0.58	3420	31.2	5.91	0.4	35.41	35.72
424.0	50000	3501	6.0	14.6	0.35	3236	29.5	5.91	0.4	32.77	33.57
424.5	45000	3998	6.0	13.4	0.37	3310	30.2	5.91	0.4	31.93	32.32
425.0	15000	5041	6.0	8.6	0.52	3207	29.2	5.91	0.4	39.31	39.63
425.5	40000	14917	6.0	8.3	0.54	3950	36.0	5.91	0.4	16.97	17.5
426.0	18000	68427	6.0	3.8	0.79	4163	37.9	5.91	0.4	8.76	11
426.5	60000	15161	6.0	9.5	0.49	3723	33.9	5.91	0.4	13.72	13.02
427.0	160000	5533	6.0	18.4	0.28	3371	30.7	5.91	0.4	16.85	16.61
427.5	4500	1834	6.0	8.1	0.55	2178	19.8	5.91	0.4	78.55	79.83
428.0	120000	17544	6.0	11.4	0.42	4138	37.7	5.91	0.4	10.86	10.2
428.5	190000	2755	6.0	24.6	0.21	3518	32.1	5.91	0.4	26.08	25.57
429.0	195000	2683	6.0	25.0	0.21	3330	30.3	5.91	0.4	24.90	24.04
429.5	5500	2771	6.0	7.5	0.57	2670	24.3	5.91	0.4	68.65	69.13

Appendix C : Method of Equivalent thickness for the Calculation of FWD Base

Large Load											
Station No	Base E2 (psi)	Subgrade E3 (psi)	H2 (in)	He (in)	Fb	P (Large) (lb)	q (Large) (psi)	R	v	Deflection (10^{-3} in)	Deflection at site (10^{-3} in)
410.0	22000	87922	6.0	3.8	0.79	9097	82.9	5.91	0.4	15.16	15.35
410.5	14000	53539	6.0	3.8	0.79	8395	76.5	5.91	0.4	22.62	23.26
411.0	22000	86490	6.0	3.8	0.79	8414	76.7	5.91	0.4	14.17	13.54
411.5	15000	32687	6.0	4.6	0.74	7818	71.2	5.91	0.4	28.35	29.6
412.0	3250	55024	6.0	2.3	0.89	6957	63.4	5.91	0.4	31.80	32.02
412.5	13500	8989	6.0	6.9	0.61	6571	59.9	5.91	0.4	57.42	57.6
413.0	40000	15929	6.0	8.2	0.54	7354	67.0	5.91	0.4	30.29	29.79
413.5	45000	14181	6.0	8.8	0.51	6893	62.8	5.91	0.4	29.36	30.25
414.0	200000	8966	6.0	16.9	0.30	6758	61.6	5.91	0.4	22.83	23.81
414.5	22000	16432	6.0	6.6	0.62	6973	63.5	5.91	0.4	34.69	33.51
415.0	22000	56942	6.0	4.4	0.75	8633	78.7	5.91	0.4	19.08	20.84
415.5	45000	45243	6.0	6.0	0.65	8538	77.8	5.91	0.4	17.11	16.25
416.0	2500	137646	6.0	1.6	0.93	8538	77.8	5.91	0.4	25.89	26.11
416.5	500000	6737	6.0	25.2	0.21	8538	77.8	5.91	0.4	25.24	18.3
417.0	32000	67703	6.0	4.7	0.73	8104	73.9	5.91	0.4	14.04	14.13
417.5	70000	37448	6.0	7.4	0.58	8477	77.3	5.91	0.4	16.47	16.12
418.0	35000	54934	6.0	5.2	0.70	8729	79.5	5.91	0.4	16.81	16.81
418.5	22000	27090	6.0	5.6	0.68	7616	69.4	5.91	0.4	27.34	28.3
419.0	35000	9557	6.0	9.2	0.50	6472	59.0	5.91	0.4	38.89	38.85
419.5	65000	18219	6.0	9.2	0.50	7476	68.1	5.91	0.4	23.78	23.97

Appendix C : Method of Equivalent thickness for the Calculation of FWD Base

420.0	225000	7186	6.0	18.9	0.27	6157	56.1	5.91	0.4	23.04	22.26
420.5	22000	51390	6.0	4.5	0.74	8268	75.3	5.91	0.4	19.53	18.18
421.0	75000	7835	6.0	12.7	0.39	6658	60.7	5.91	0.4	34.71	35.18
421.5	12500	11248	6.0	6.2	0.64	6814	62.1	5.91	0.4	52.84	53.97
422.0	60000	4408	6.0	14.3	0.35	6003	54.7	5.91	0.4	49.11	48.1
422.5	40000	4307	6.0	12.6	0.39	5736	52.3	5.91	0.4	54.99	55.26
423.0	50000	10348	6.0	10.1	0.46	6750	61.5	5.91	0.4	33.96	33.84
423.5	8000	7964	6.0	6.0	0.65	6258	57.0	5.91	0.4	70.99	69.38
424.0	25000	3624	6.0	11.4	0.42	5153	47.0	5.91	0.4	65.25	66
424.5	20000	3724	6.0	10.5	0.45	5299	48.3	5.91	0.4	71.36	70.98
425.0	10000	5430	6.0	7.4	0.58	5606	51.1	5.91	0.4	75.52	78.72
425.5	20000	14585	6.0	6.7	0.62	6674	60.8	5.91	0.4	37.10	38.2
426.0	5000	63729	6.0	2.6	0.87	7945	72.4	5.91	0.4	28.03	27.44
426.5	65000	12931	6.0	10.3	0.46	7262	66.2	5.91	0.4	28.83	29.51
427.0	80000	5568	6.0	14.6	0.35	5824	53.1	5.91	0.4	37.00	36.15
427.5	28000	5871	6.0	10.1	0.47	4783	43.6	5.91	0.4	42.61	42.89
428.0	50000	18520	6.0	8.4	0.53	7444	67.8	5.91	0.4	25.70	24.11
428.5	45000	4092	6.0	13.3	0.37	4958	45.2	5.91	0.4	47.12	46.16
429.0	40000	5109	6.0	11.9	0.41	5129	46.7	5.91	0.4	44.04	44.05
429.5	2000	4932	6.0	4.4	0.75	4962	45.2	5.91	0.4	124.48	128

APPENDIX D: Result of DCP Test on Subgrade at each Station

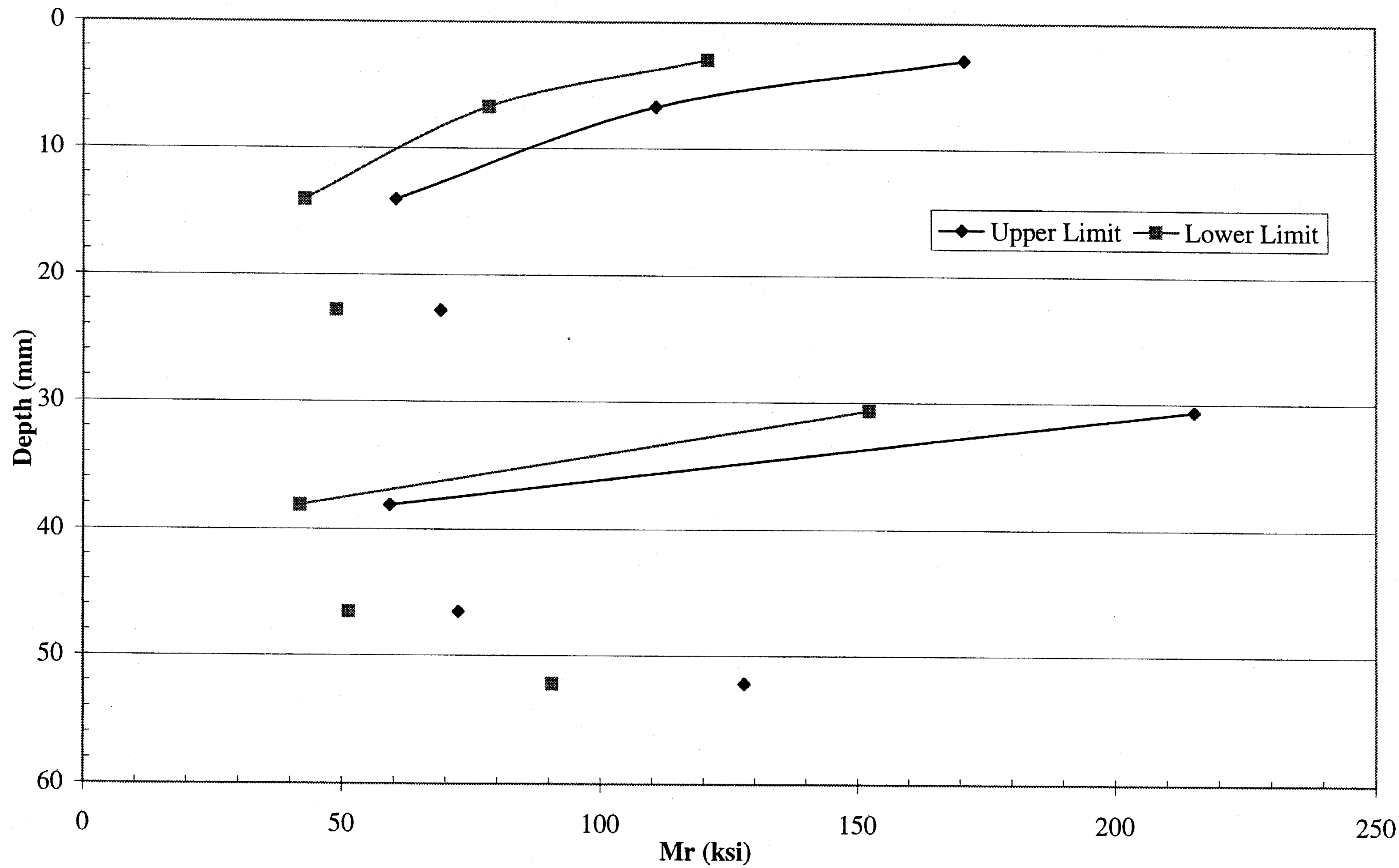

Figure D.1: Results of DCP Test on Subgrade at Station 410+00

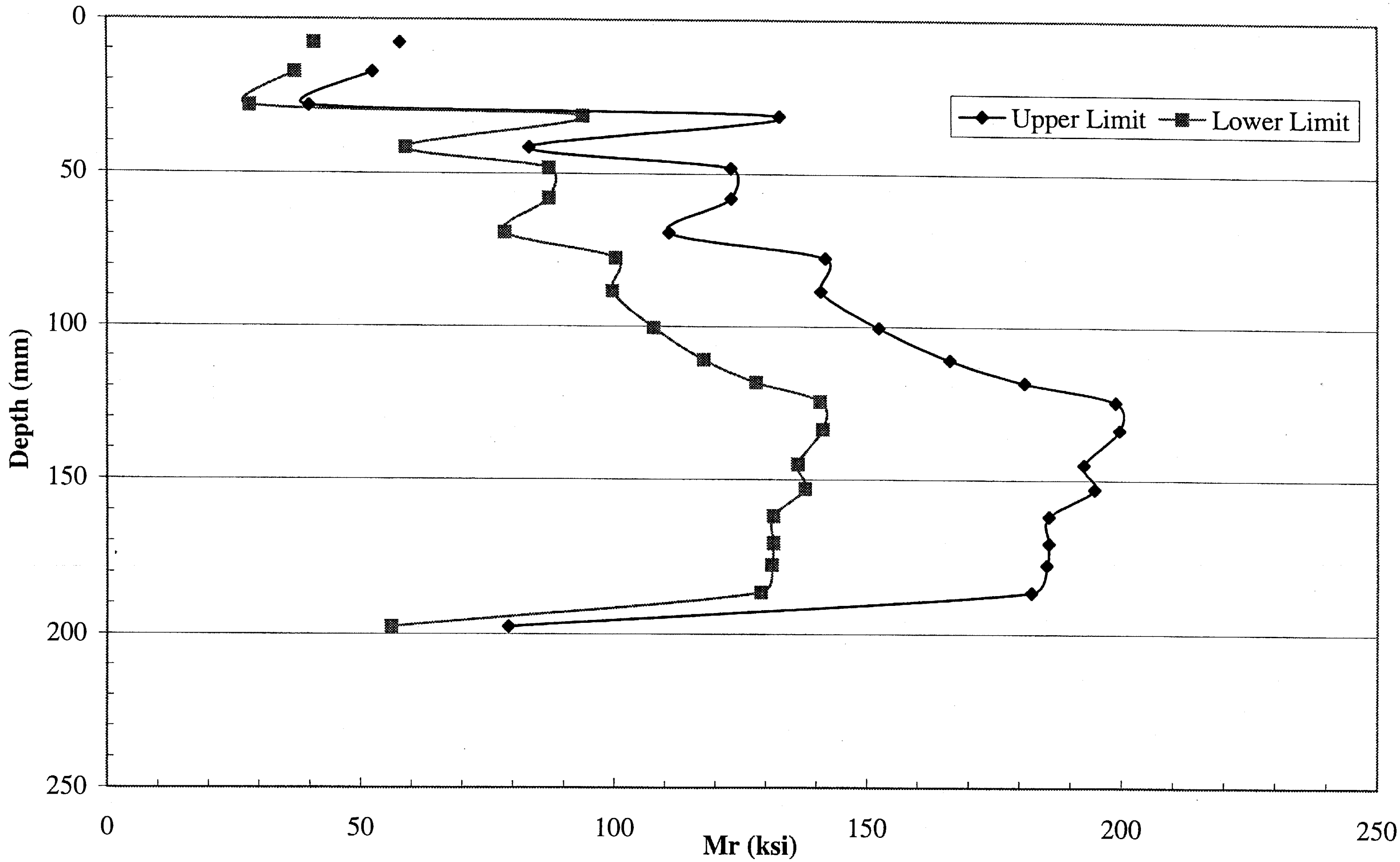

Figure D.2: Results of DCP Test on Subgrade at Station 410+50

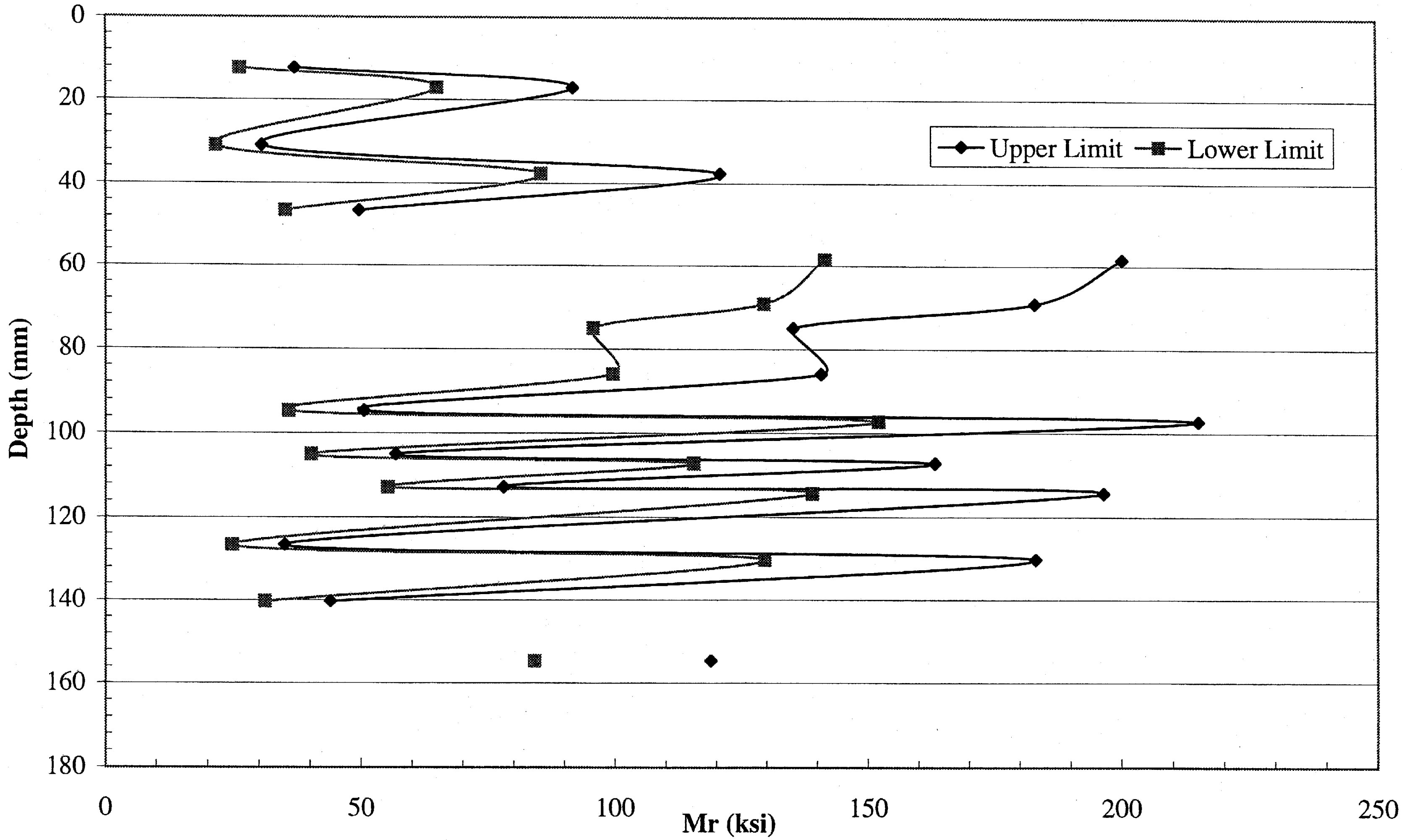

Figure D.3: Results of DCP Test on Subgrade at Station 411+00

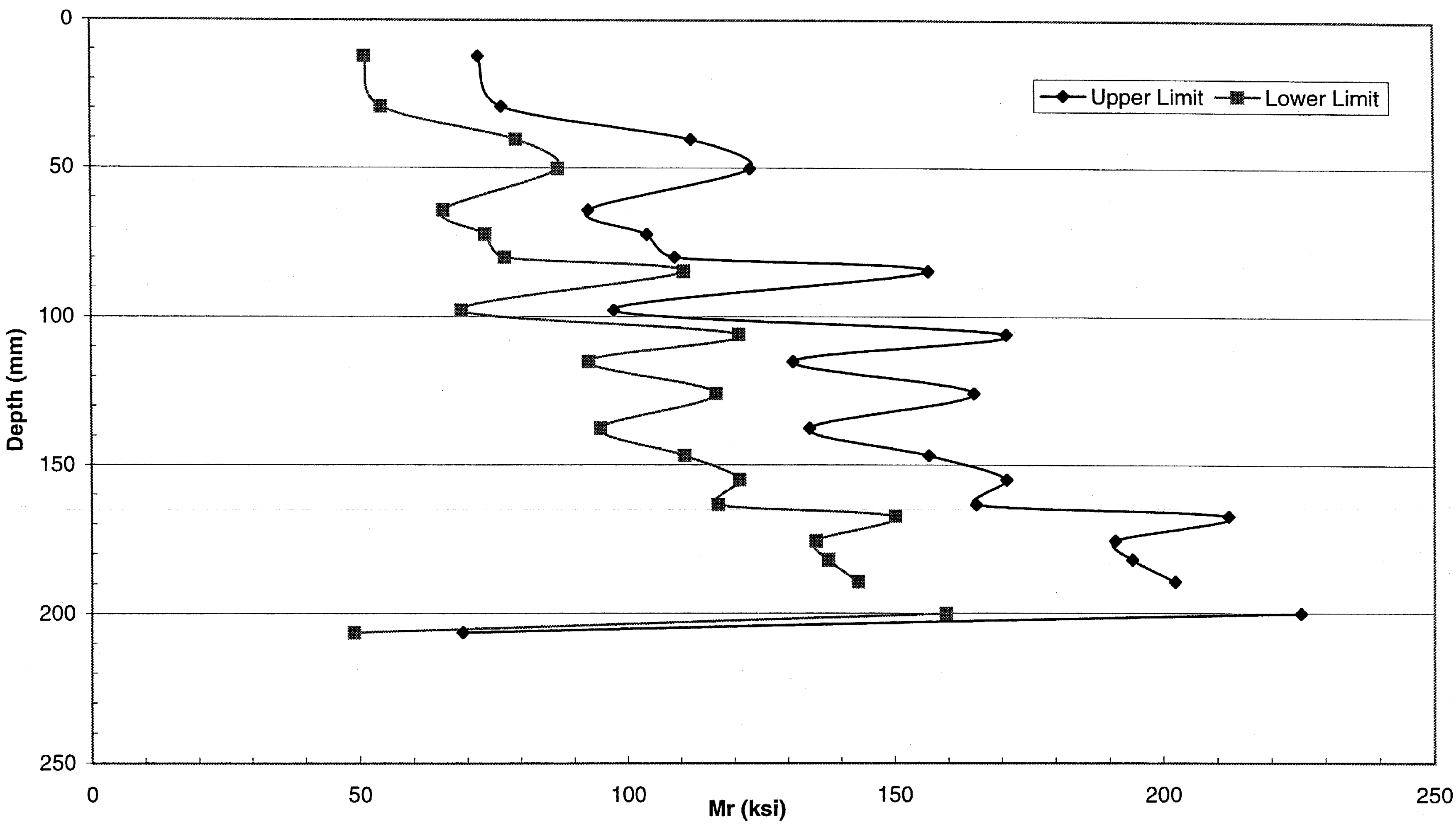

Figure D.4: Results of DCP Test on Subgrade at Station 411+50

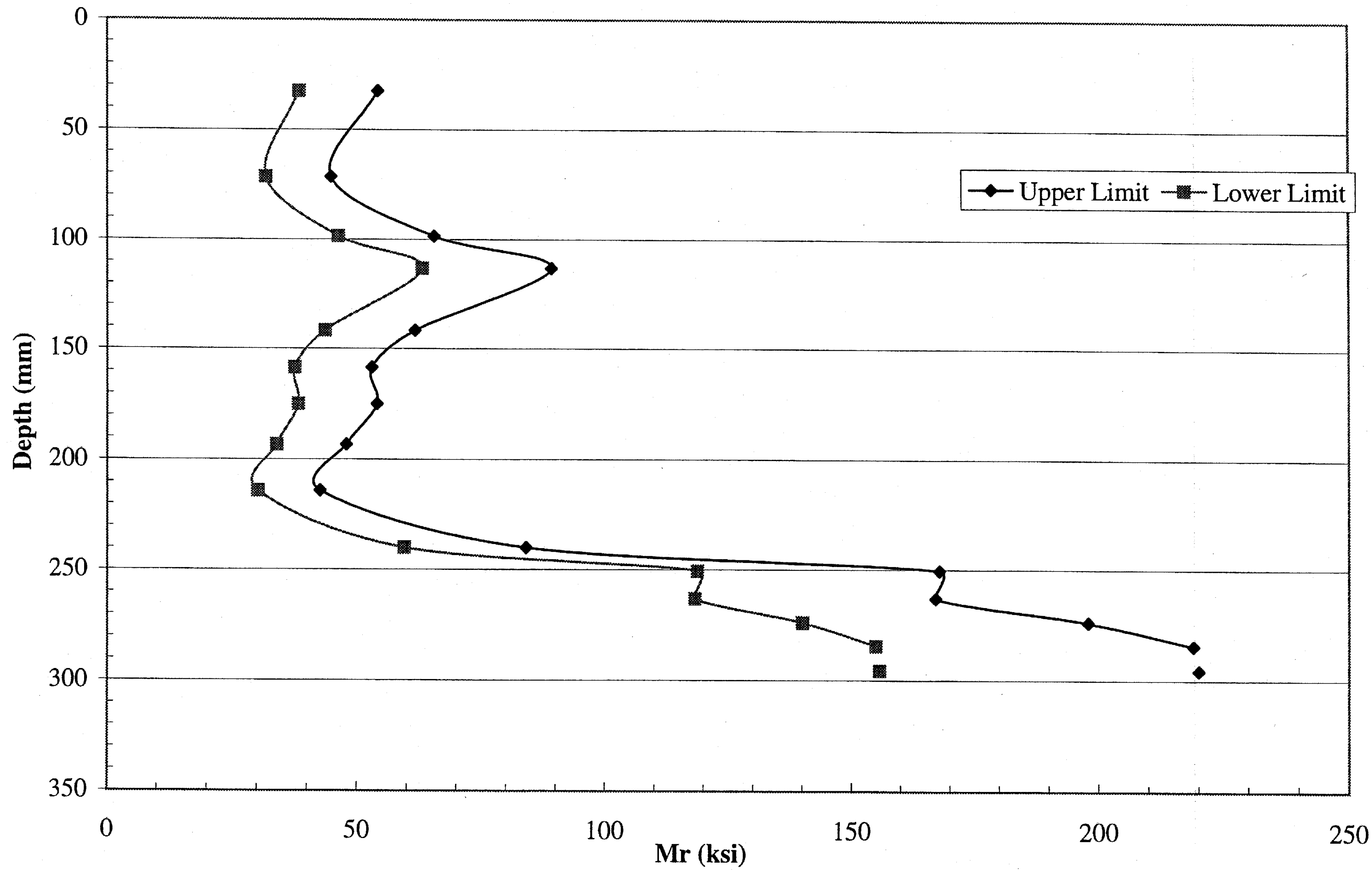

Figure D.5: Results of DCP Test on Subgrade at Station 412+00

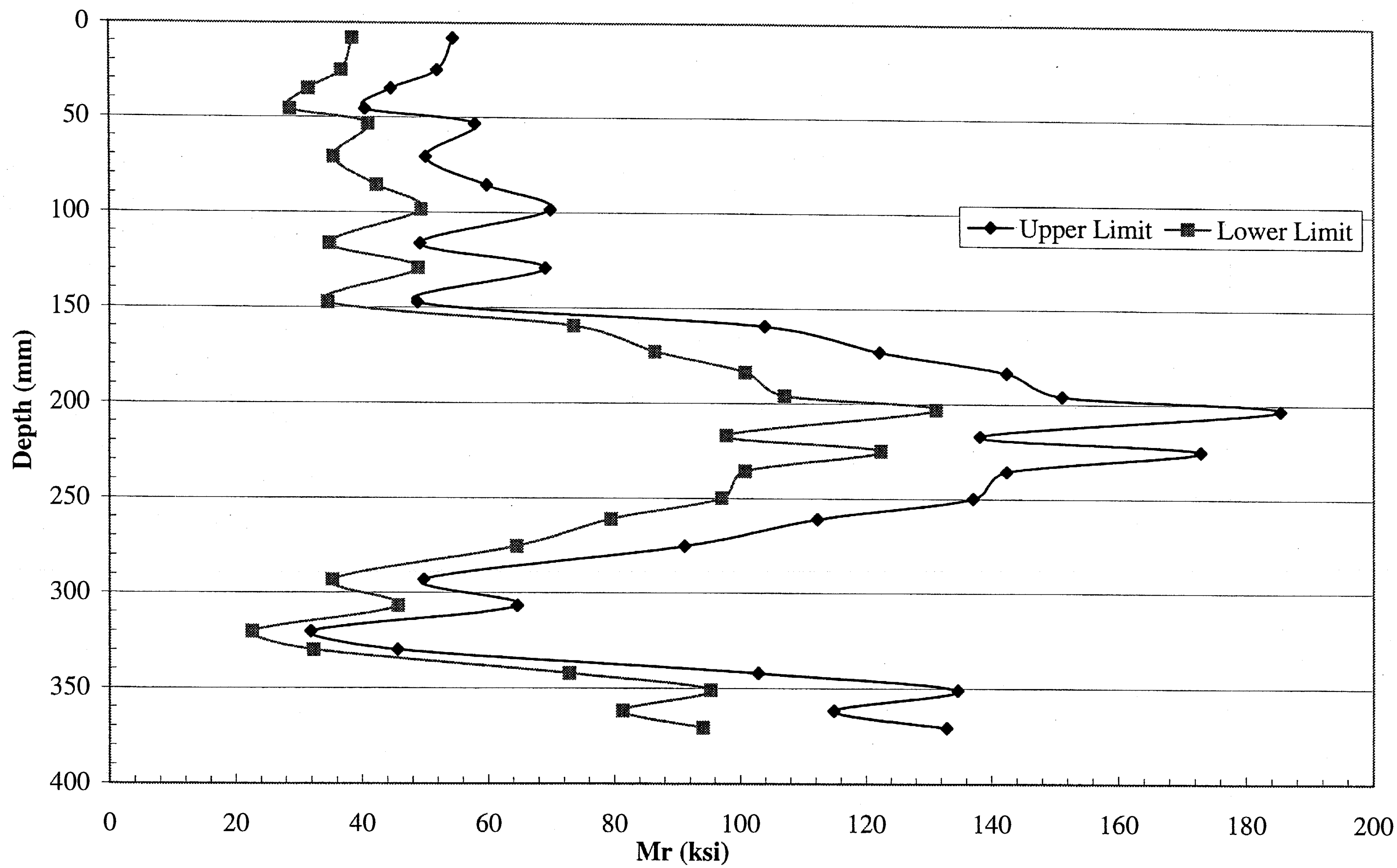

Figure D.6: Results of DCP Test on Subgrade at Station 412+50

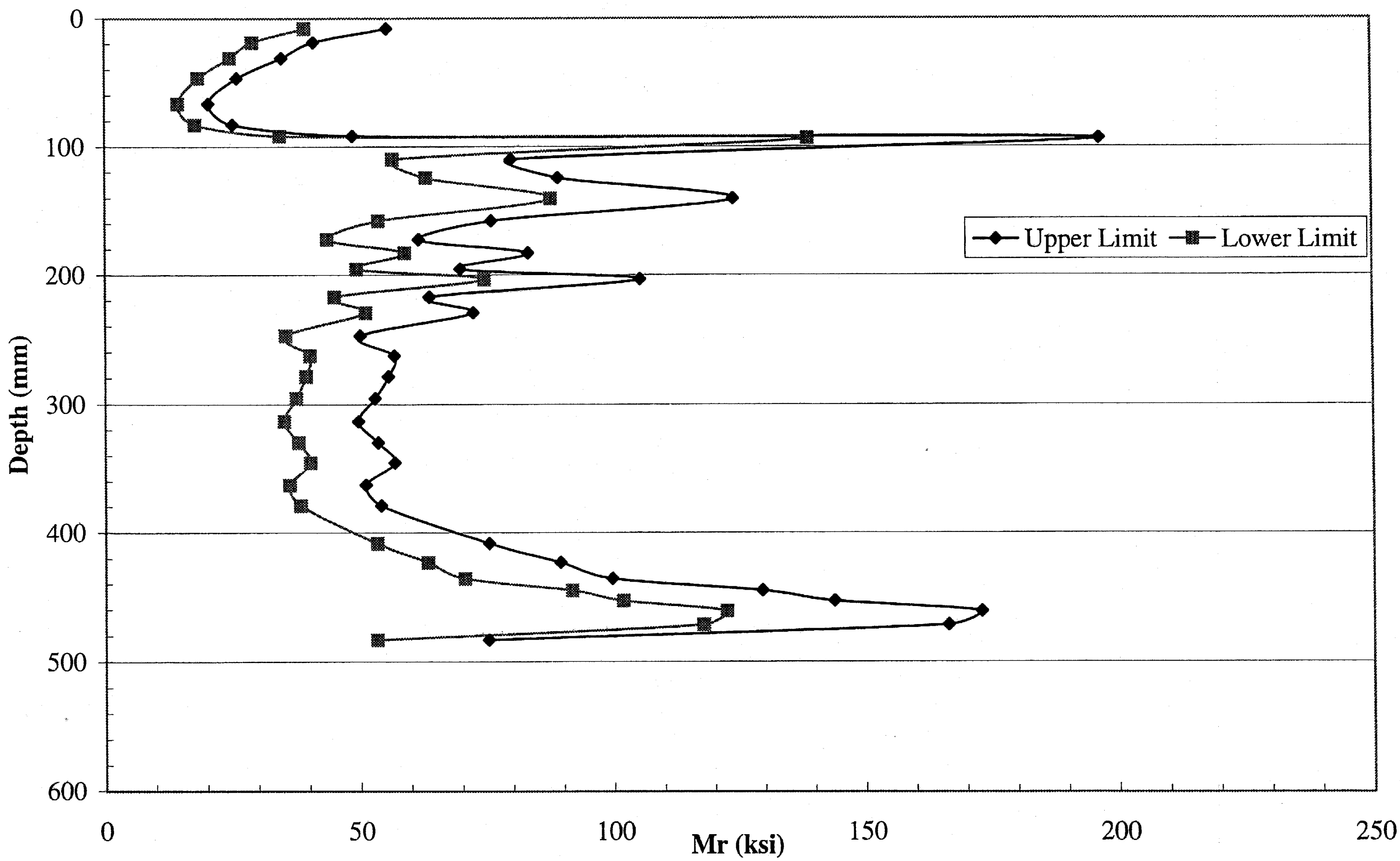

Figure D.7: Results of DCP Test on Subgrade at Station 413+00

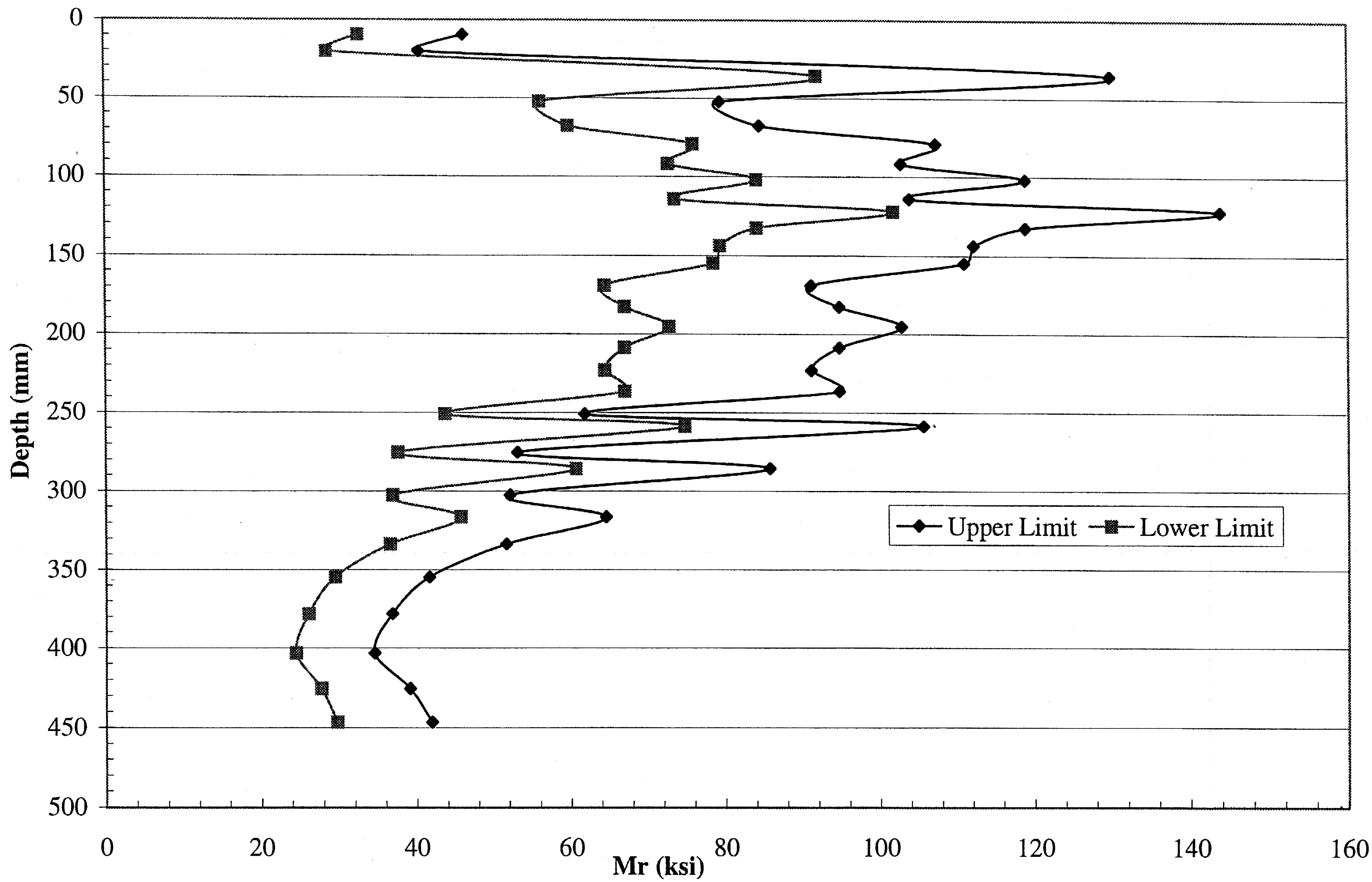

Figure D.8: Results of DCP Test on Subgrade at Station 413+50

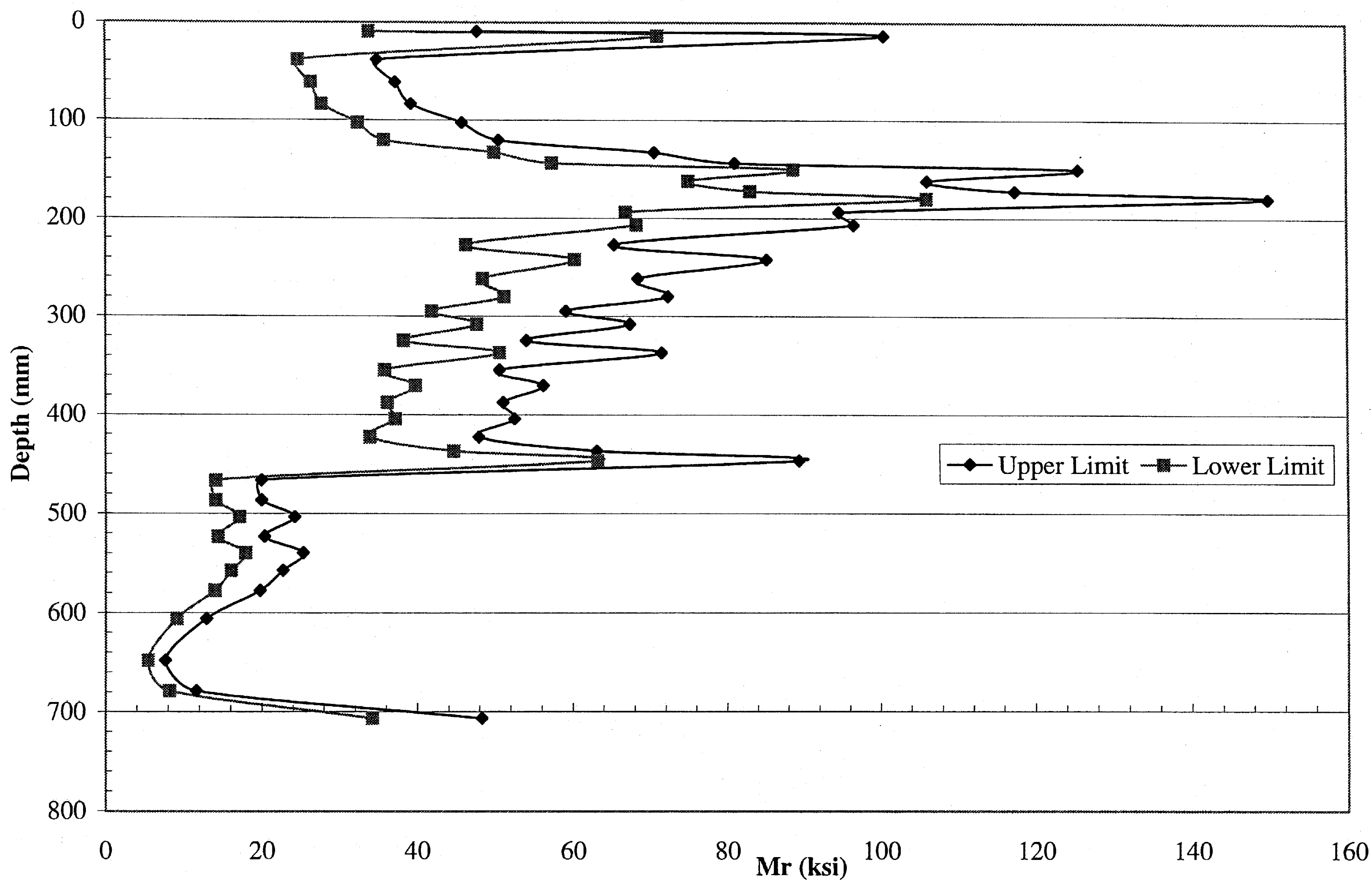

Figure D.9: Results of DCP Test on Subgrade at Station 414+00

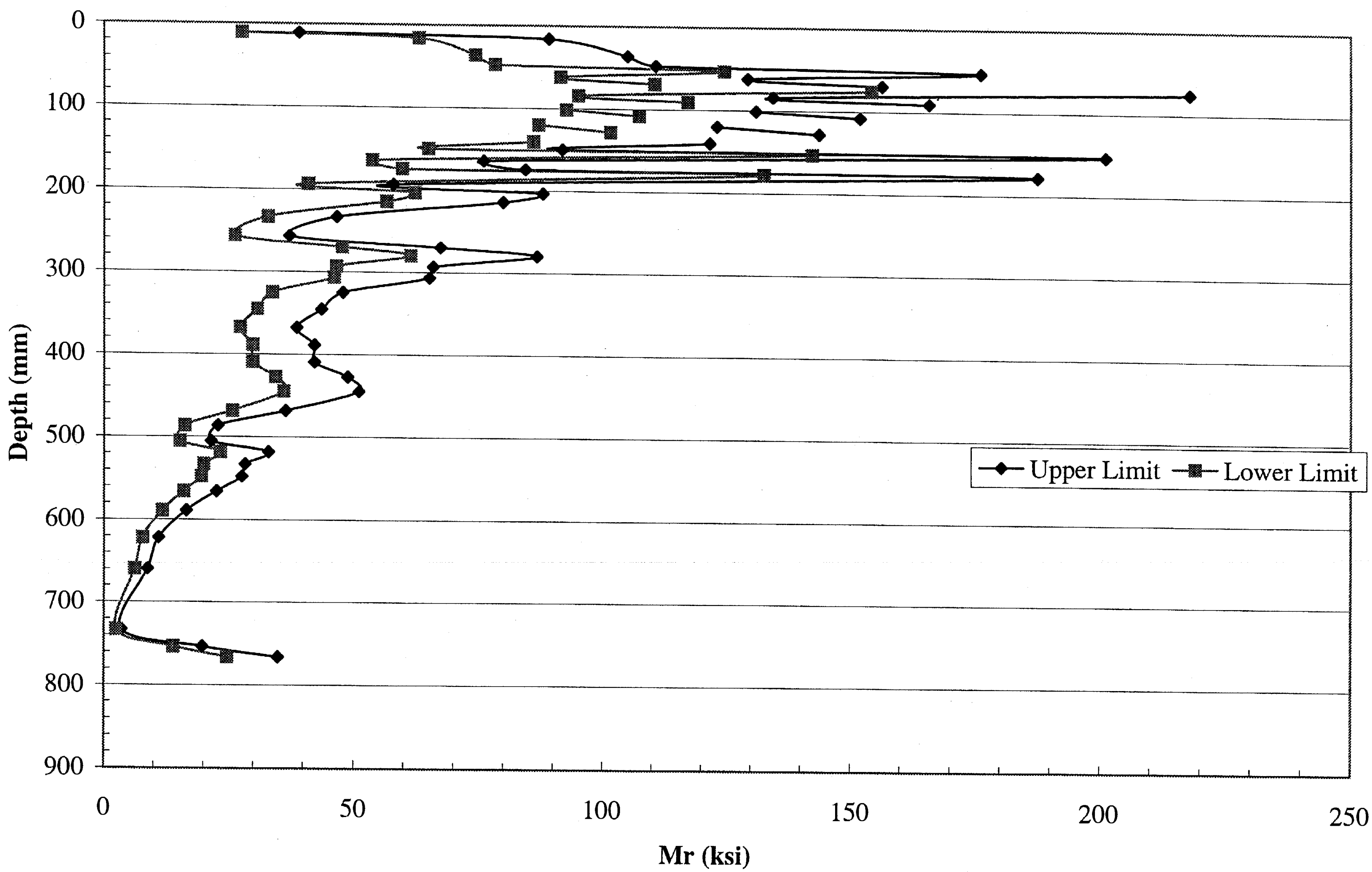

Figure D.10: Results of DCP Test on Subgrade at Station 414+50

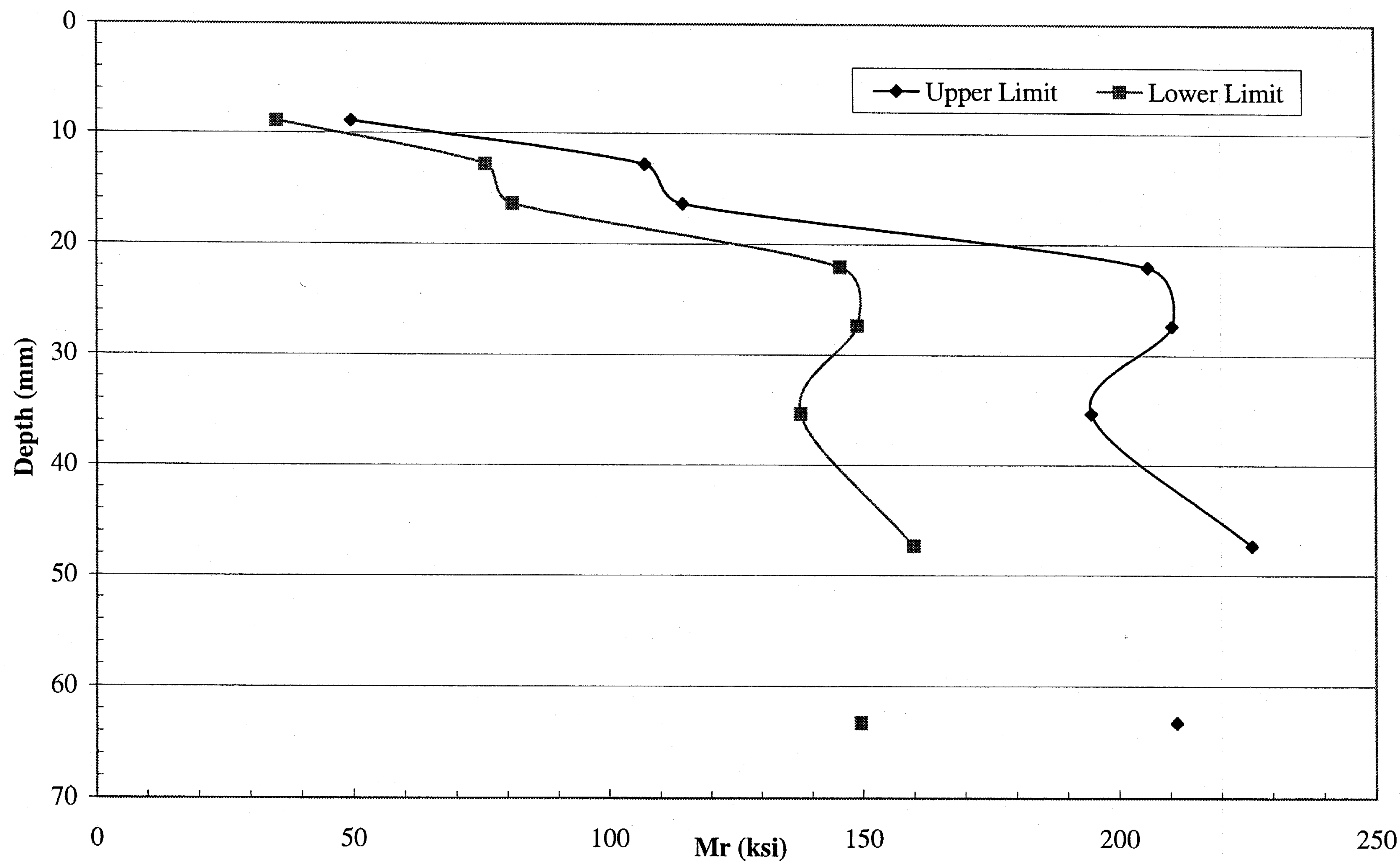

Figure D.11: Results of DCP Test on Subgrade at Station 415+00

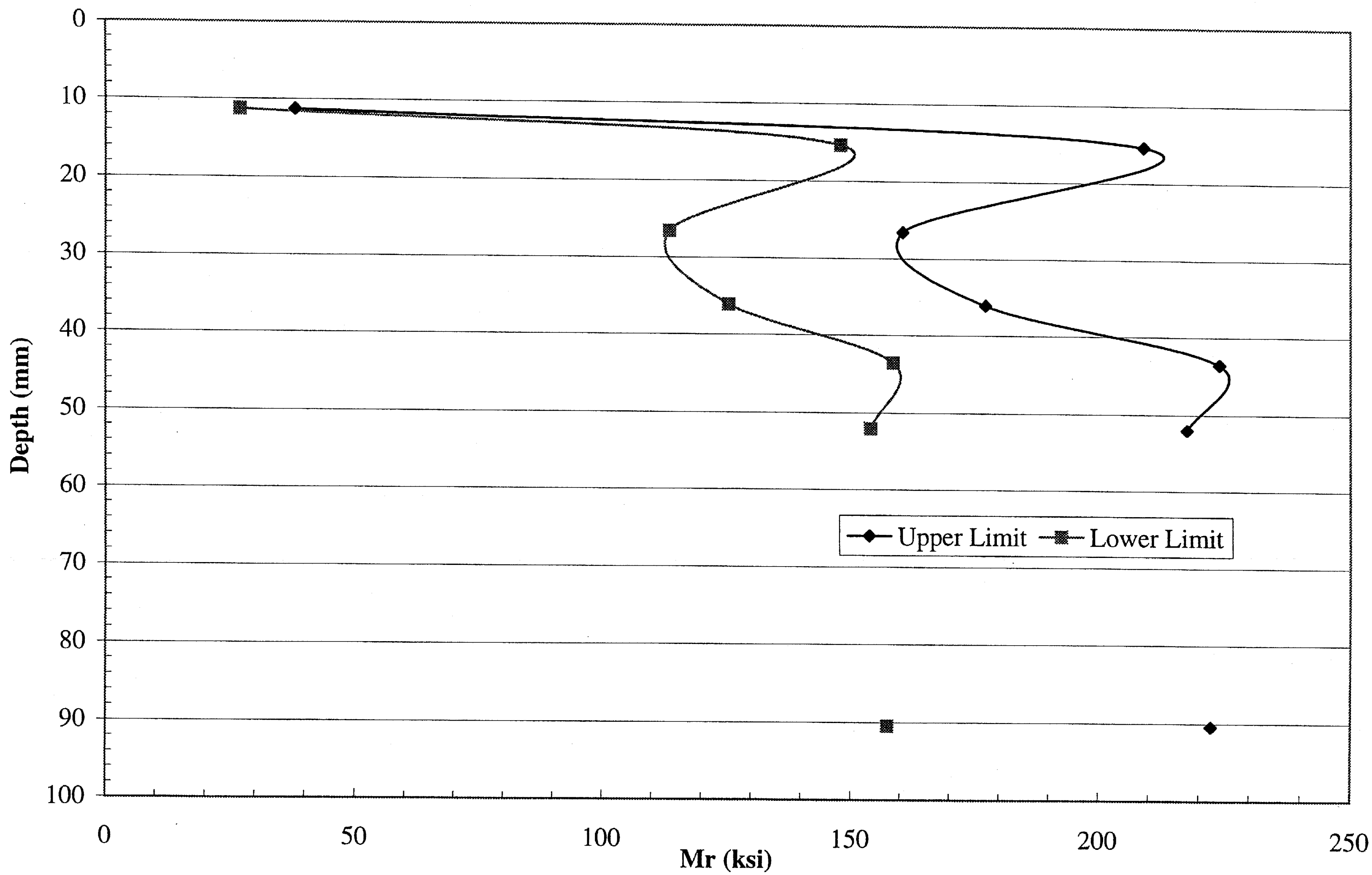

Figure D.12: Results of DCP Test on Subgrade at Station 415+50

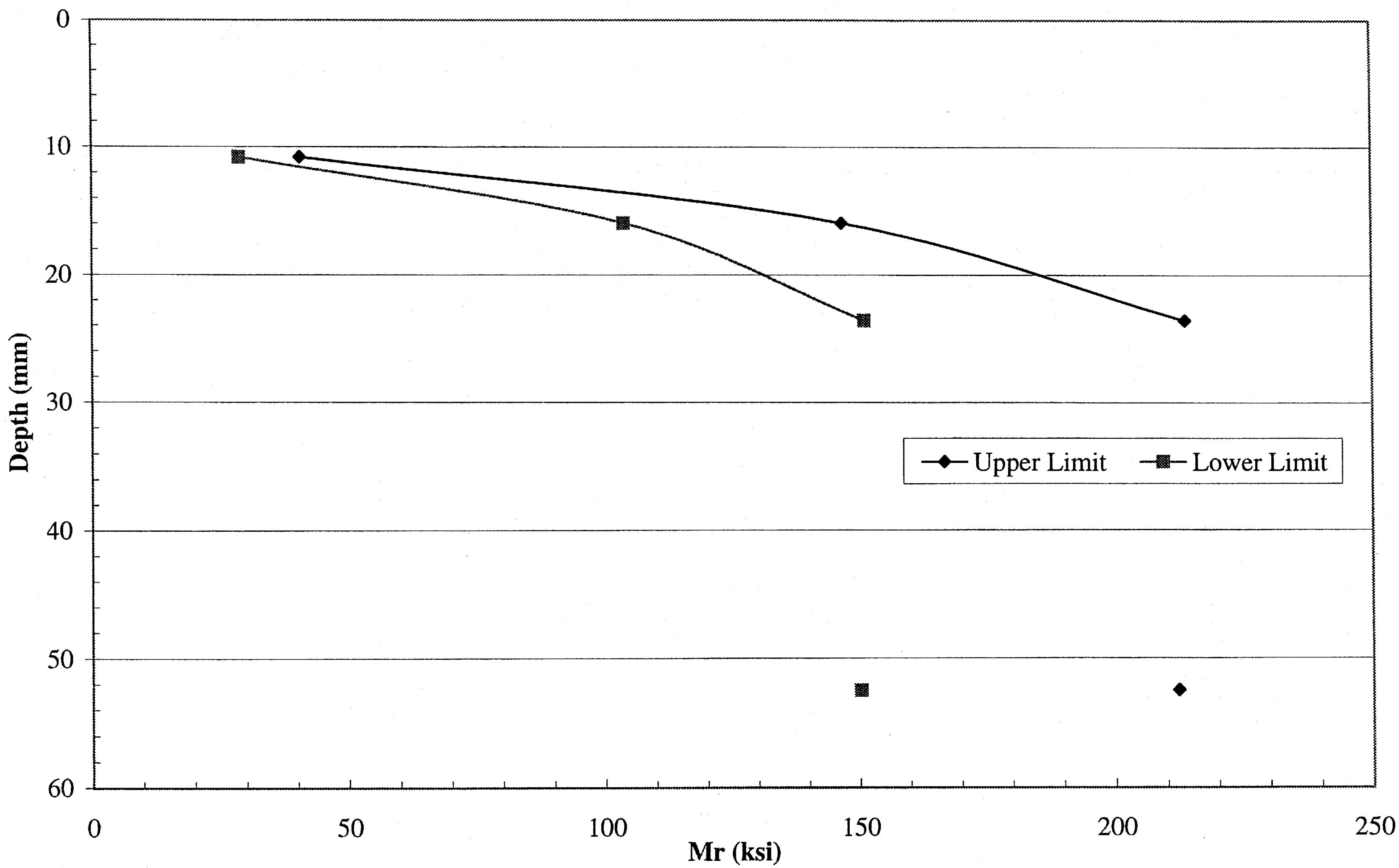

Figure D.13: Results of DCP Test on Subgrade at Station 416+00

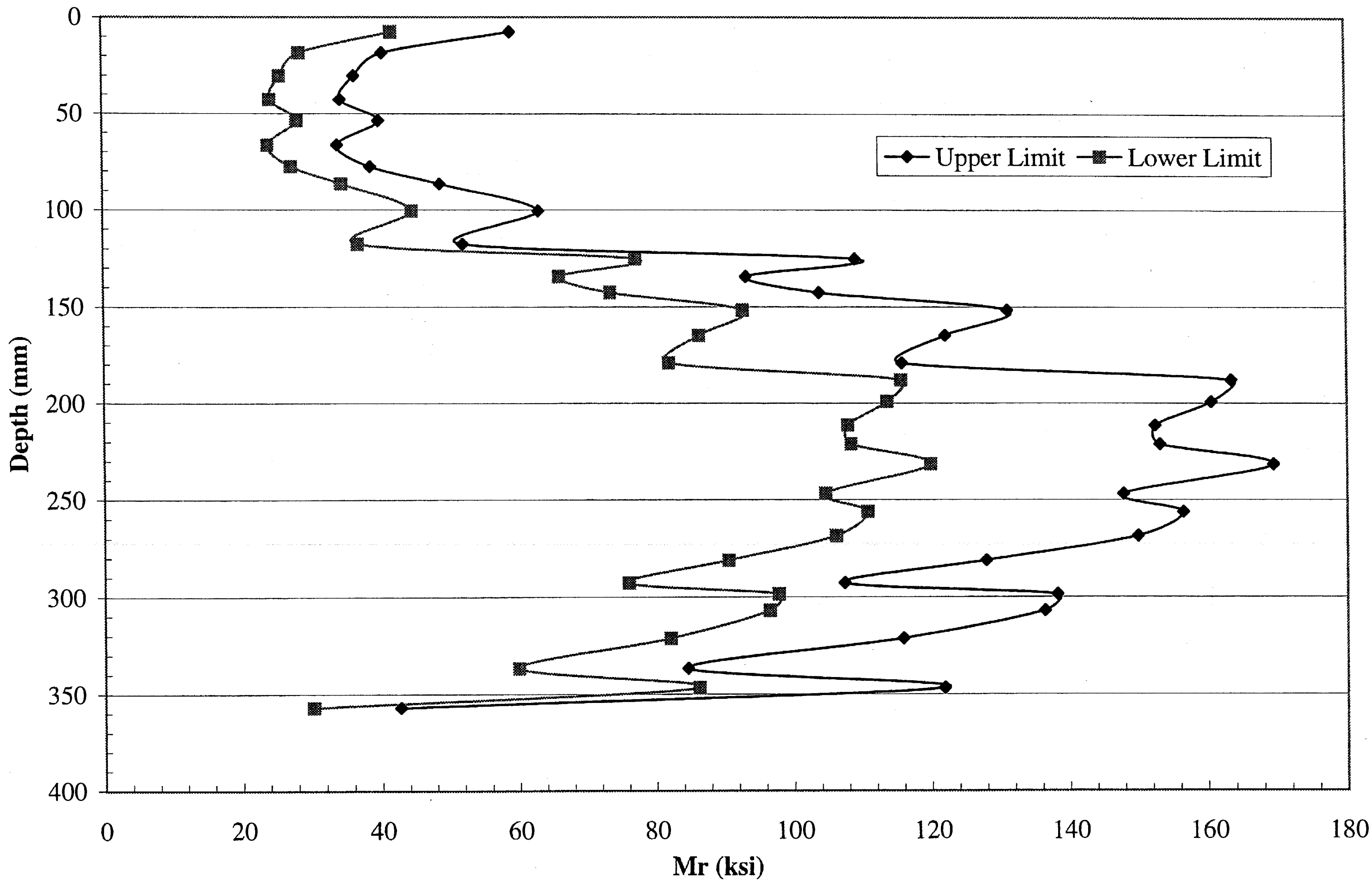

Figure D.14: Results of DCP Test on Subgrade at Station 416+50

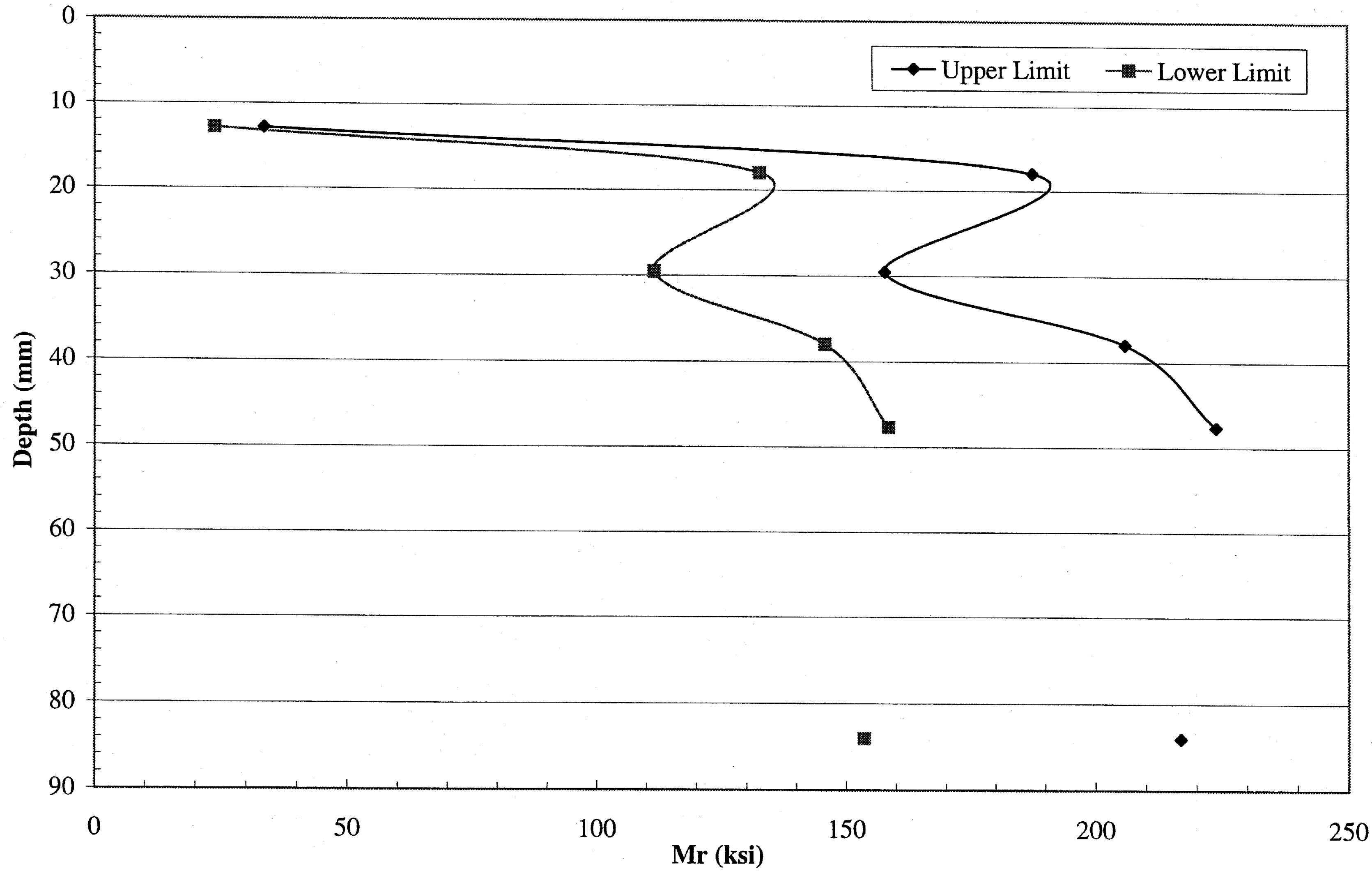

Figure D.15: Results of DCP Test on Subgrade at Station 417+00

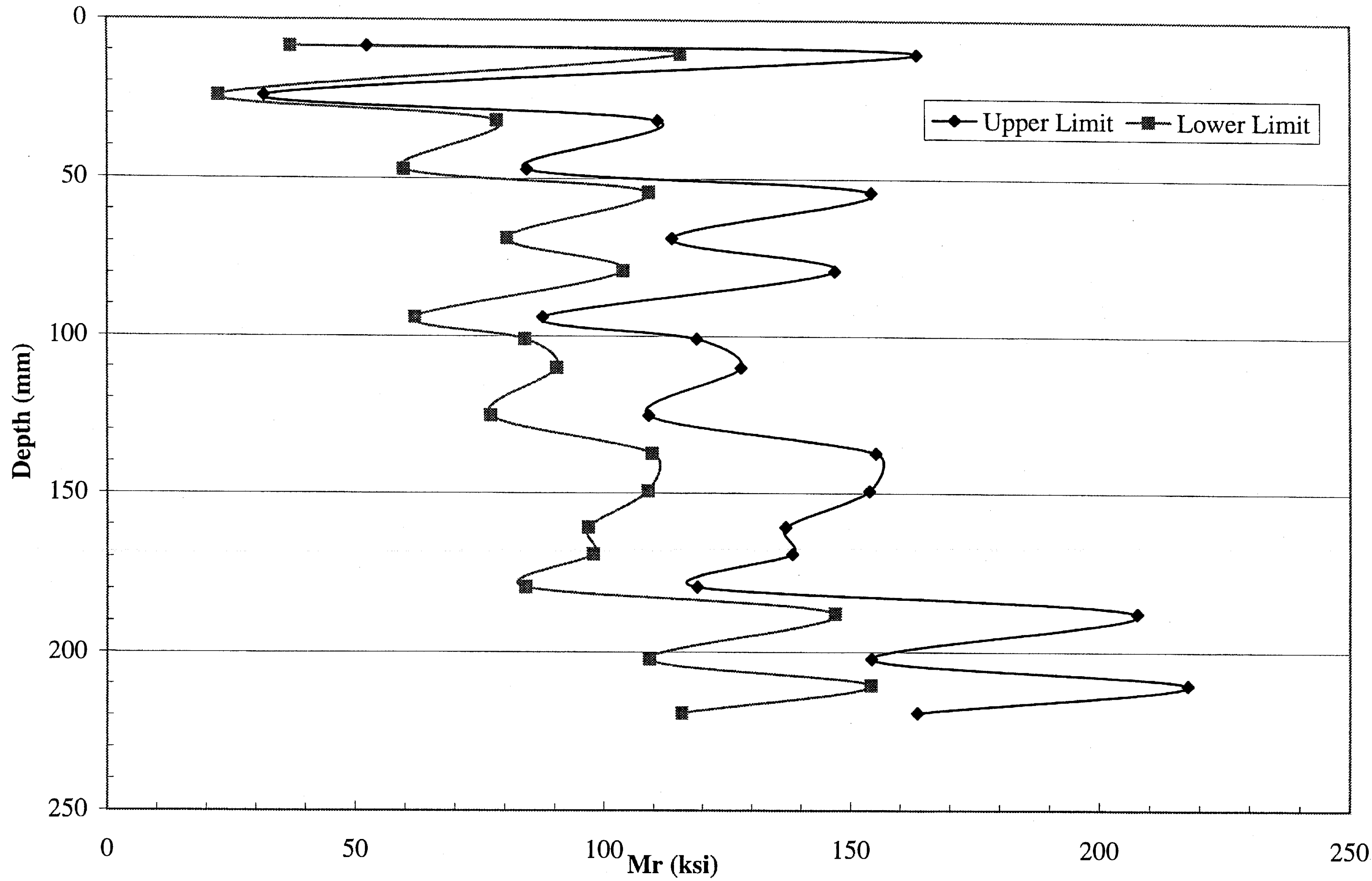

Figure D.16: Results of DCP Test on Subgrade at Station 417+50

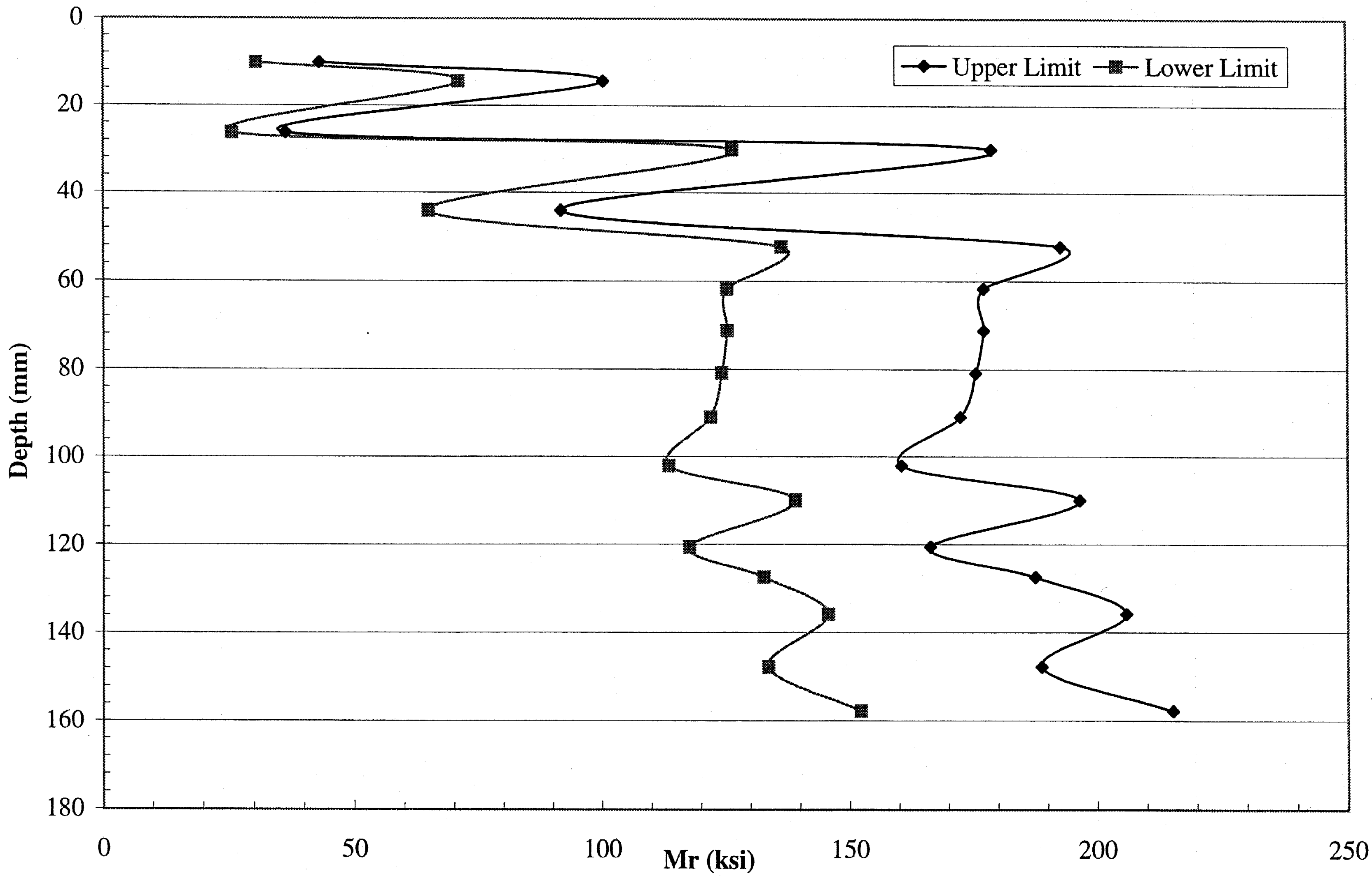

Figure D.17: Results of DCP Test on Subgrade at Station 418+00

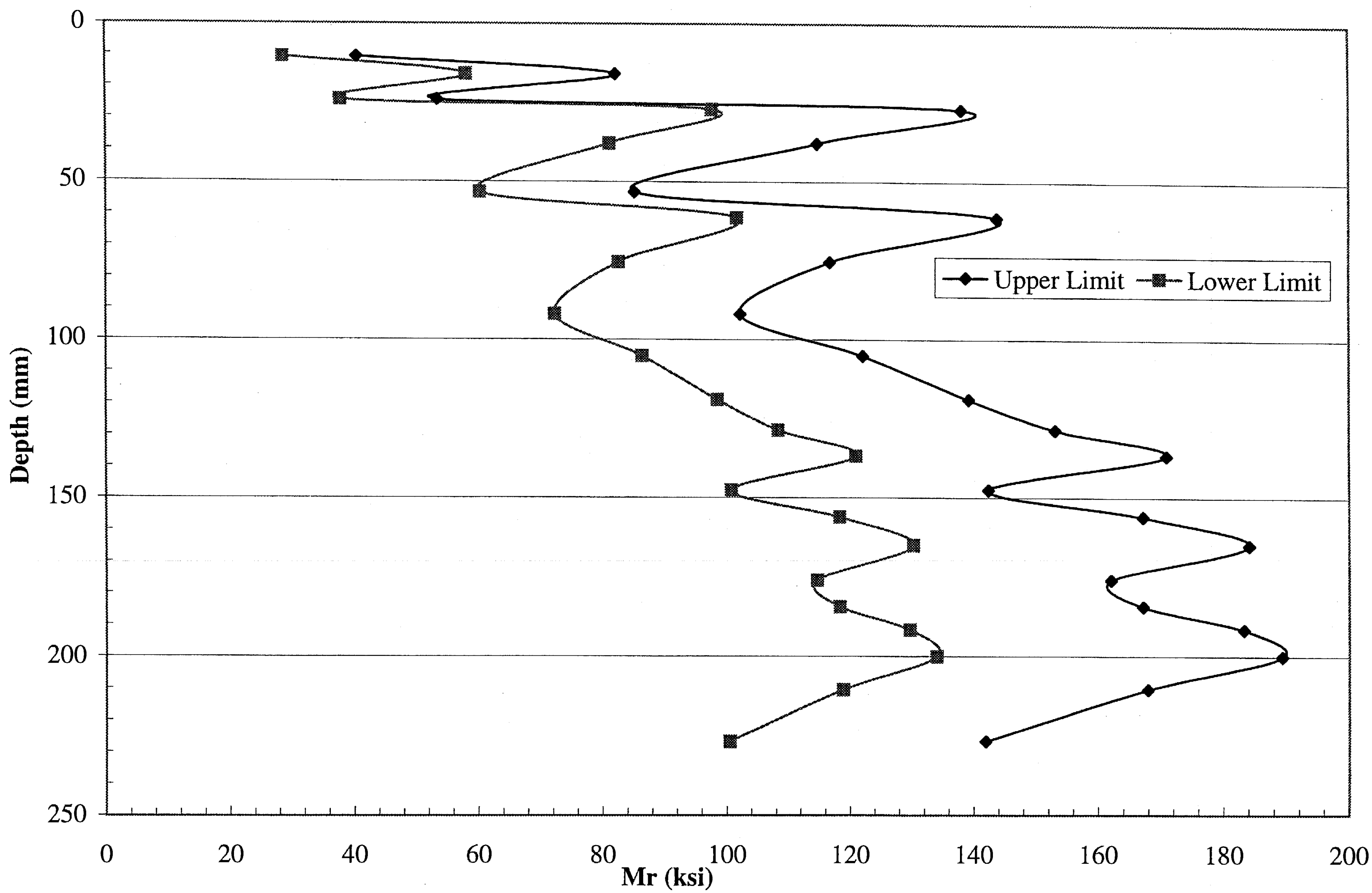

Figure D.18: Results of DCP Test on Subgrade at Station 418+50

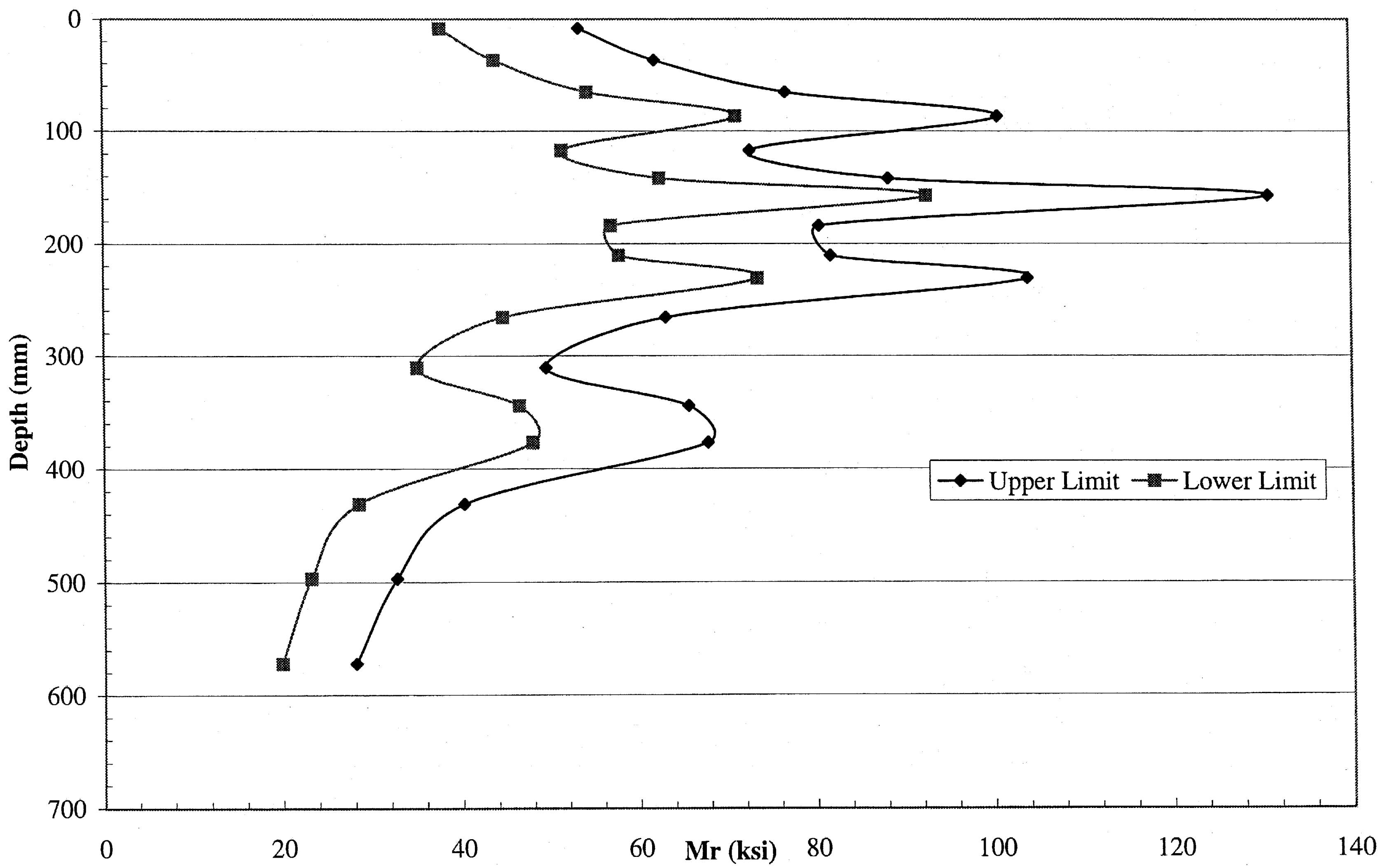

Figure D.19: Results of DCP Test on Subgrade at Station 419+00

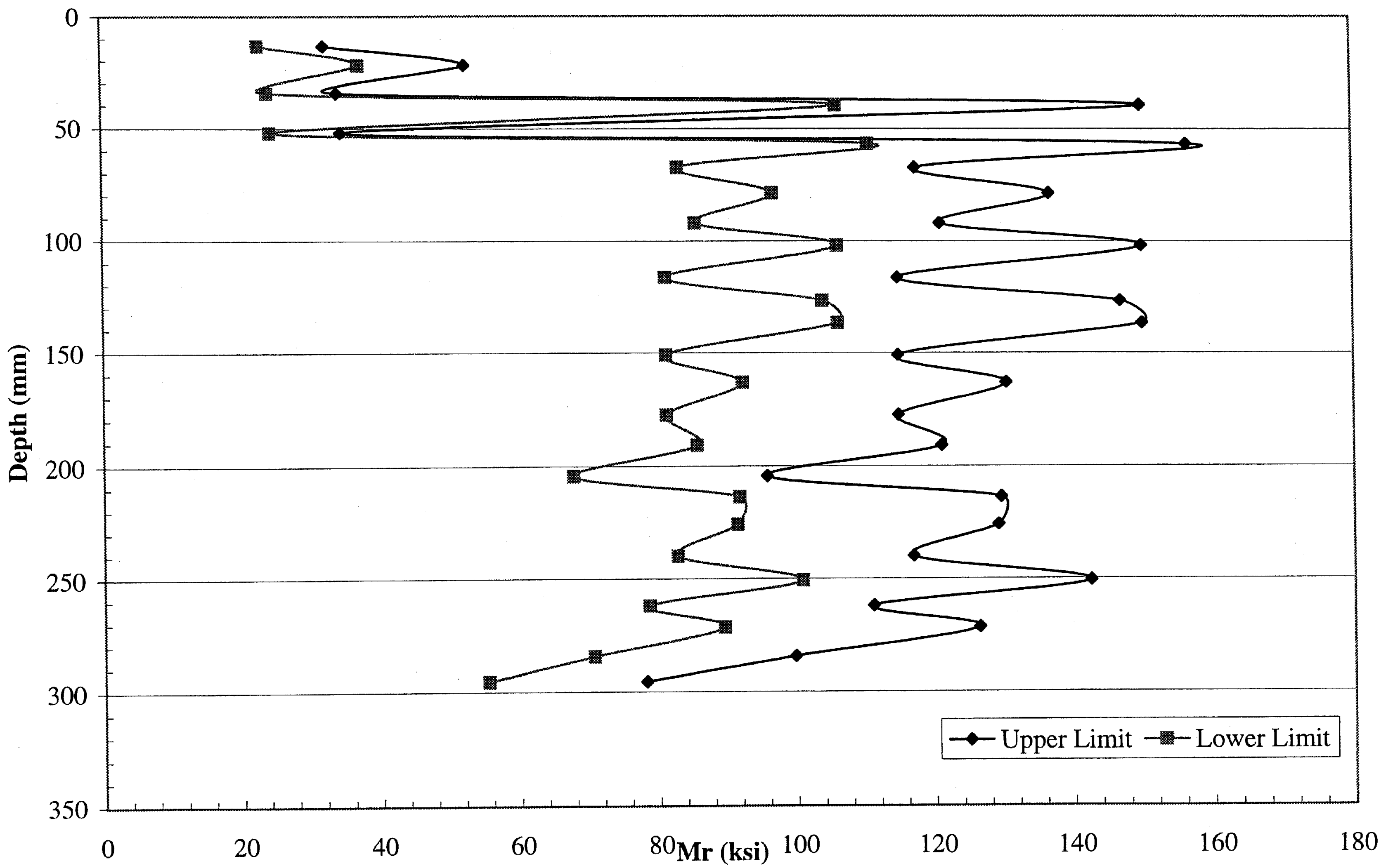

Figure D.20: Results of DCP Test on Subgrade at Station 419+50

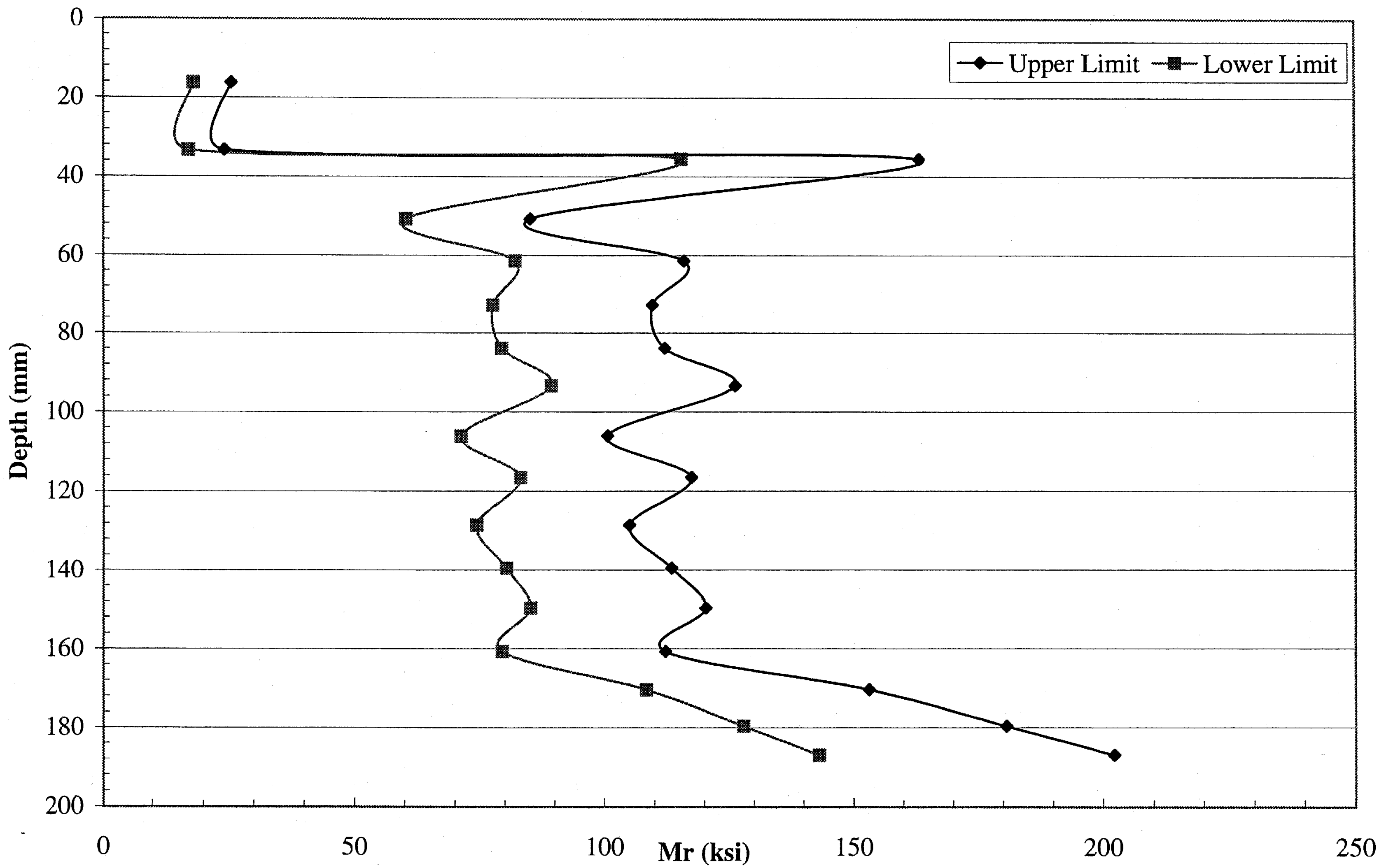

Figure D.21: Results of DCP Test on Subgrade at Station 420+00

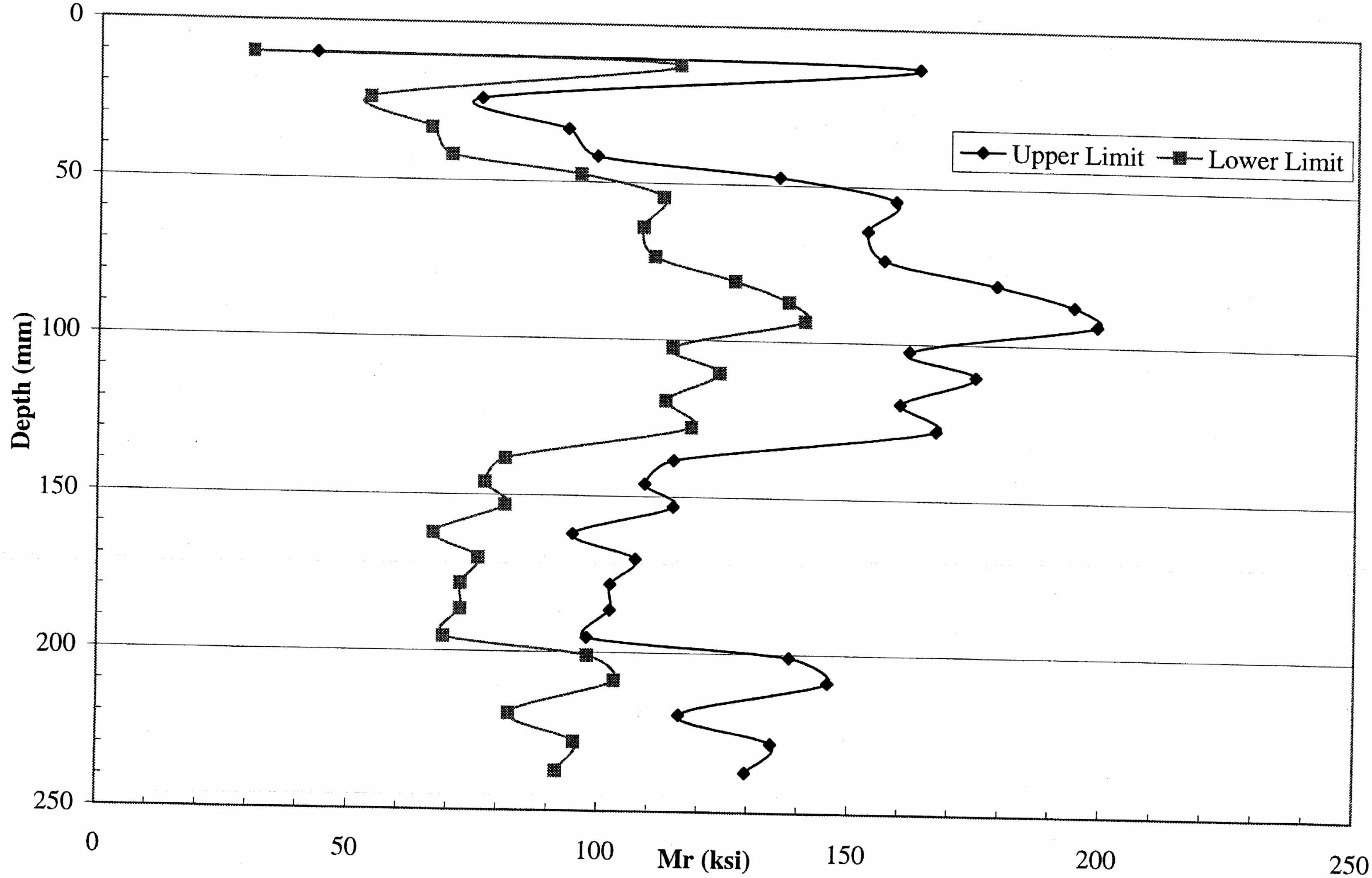

Figure D.22: Results of DCP Test on Subgrade at Station 420+50

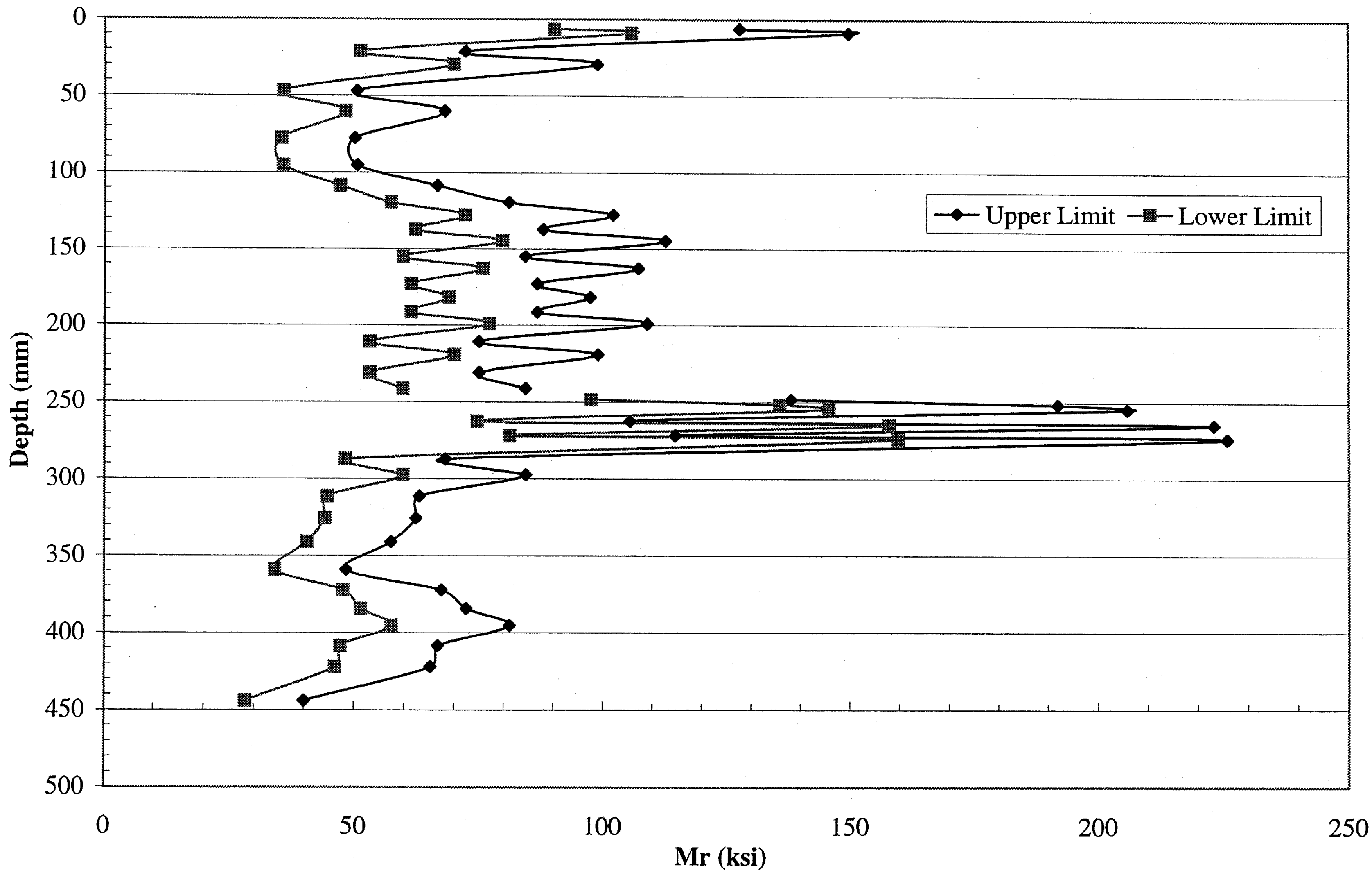

Figure D.23: Results of DCP Test on Subgrade at Station 421+00

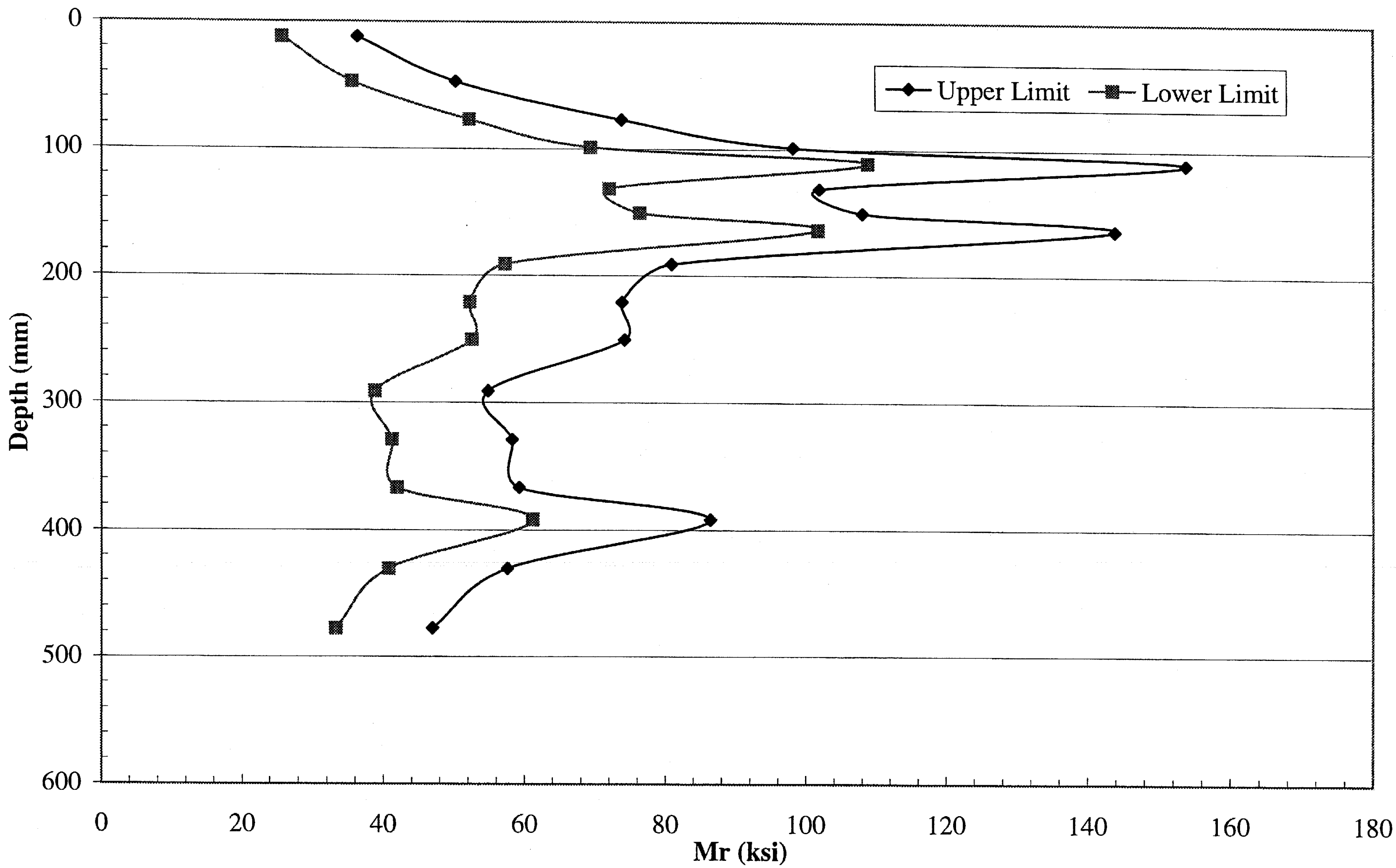

Figure D.24: Results of DCP Test on Subgrade at Station 421+50

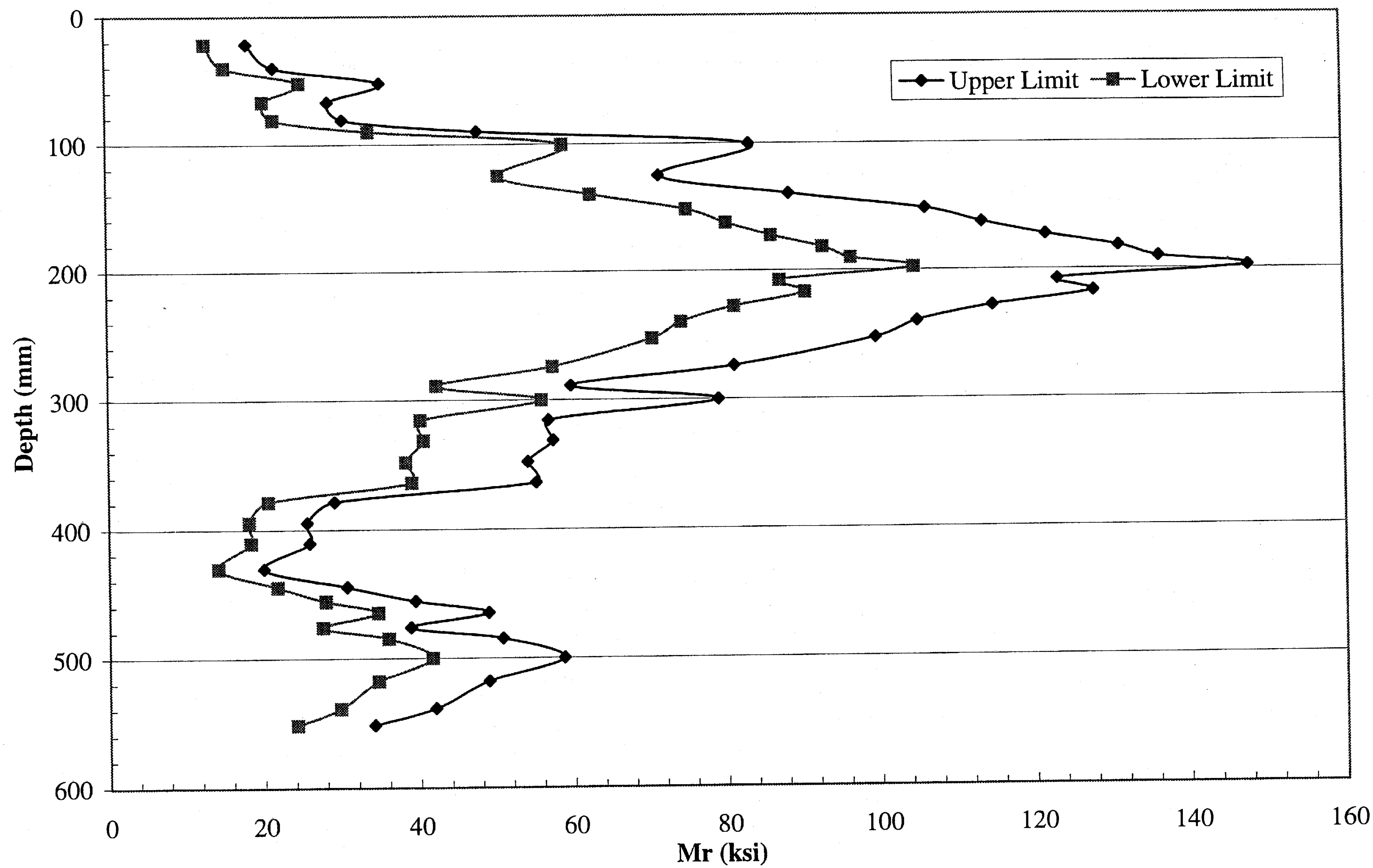

Figure D.25: Results of DCP Test on Subgrade at Station 422+00

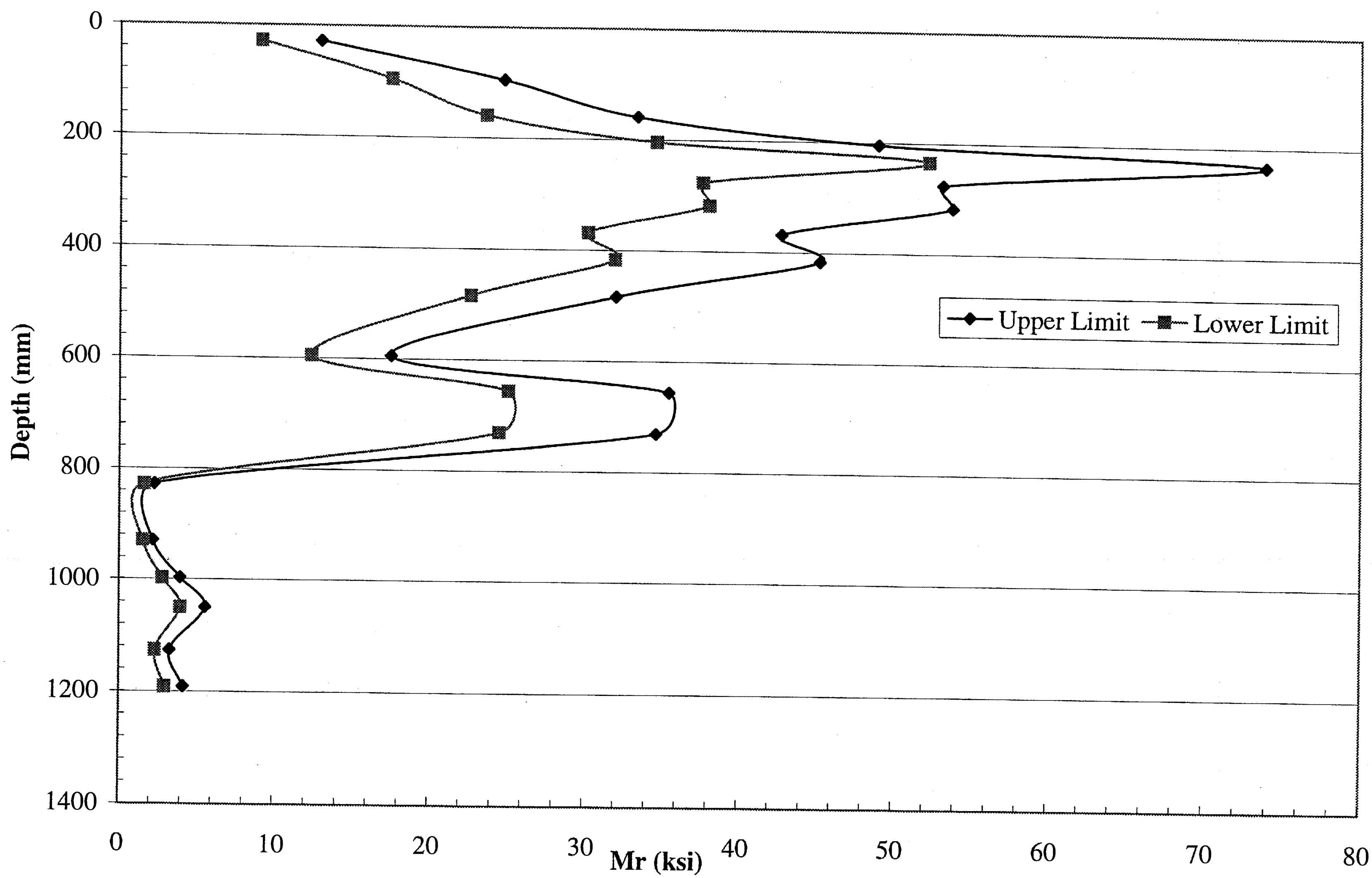

Figure D.26: Results of DCP Test on Subgrade at Station 422+50

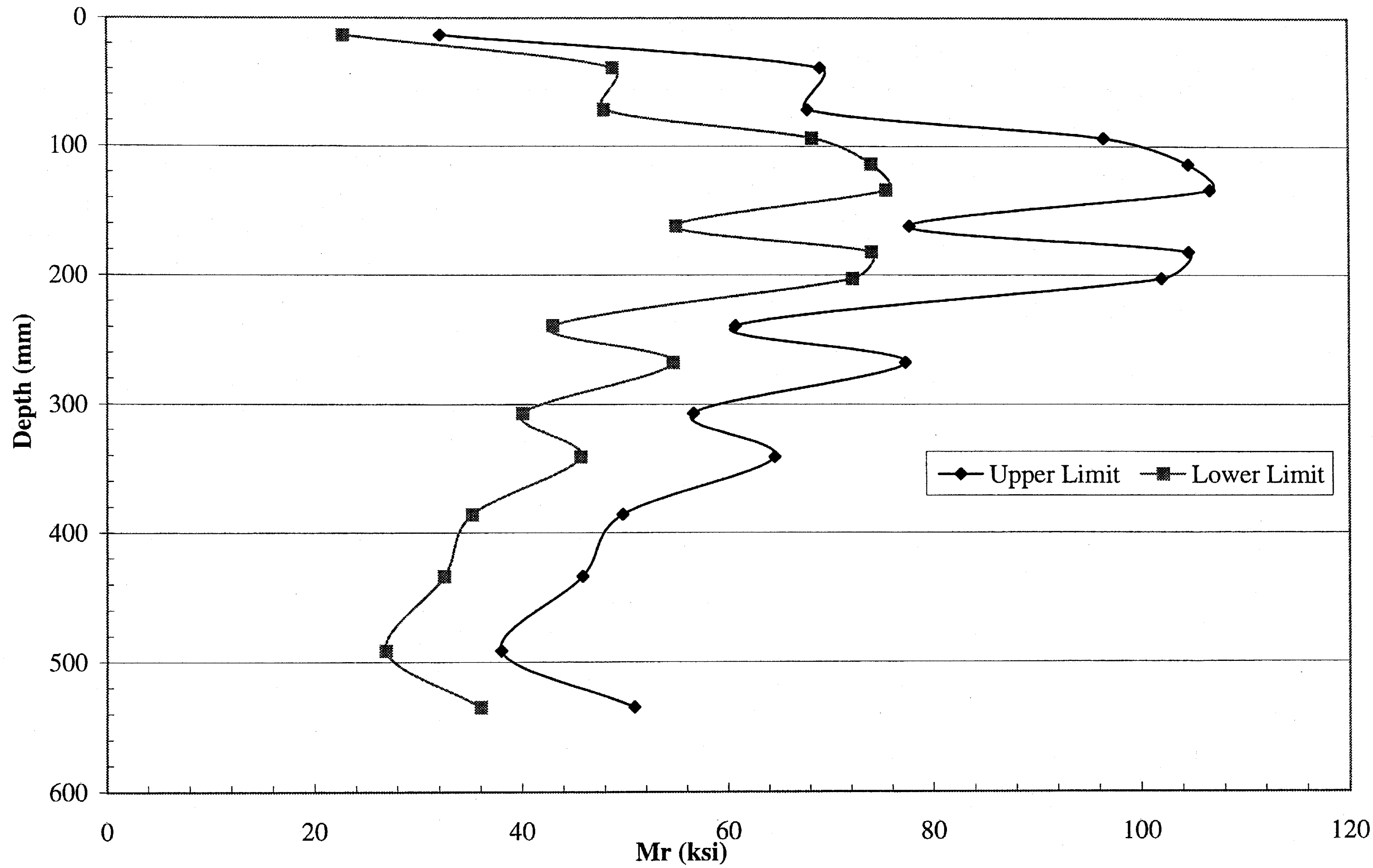

Figure D.27: Results of DCP Test on Subgrade at Station 423+00

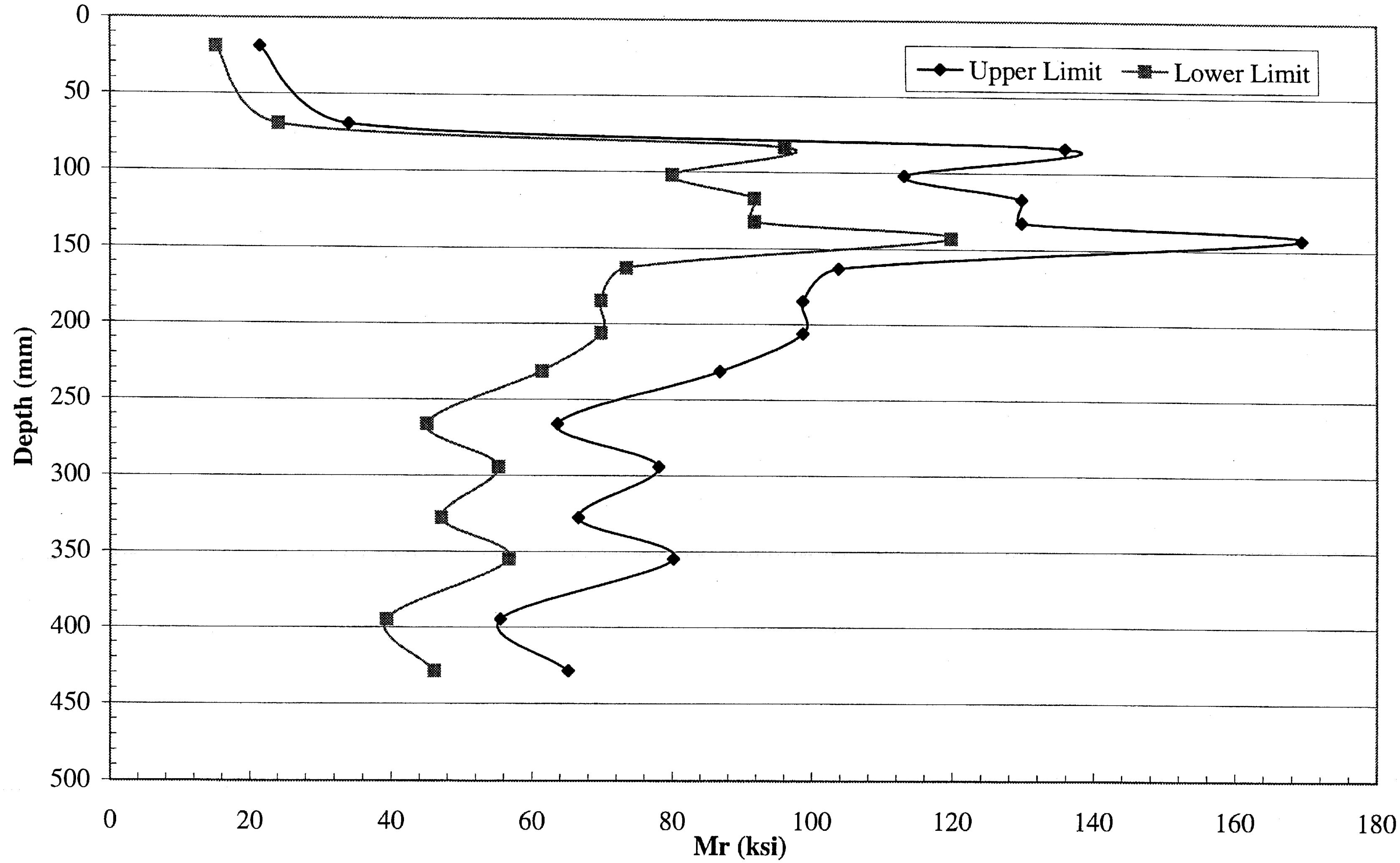

Figure D.28: Results of DCP Test on Subgrade at Station 423+50

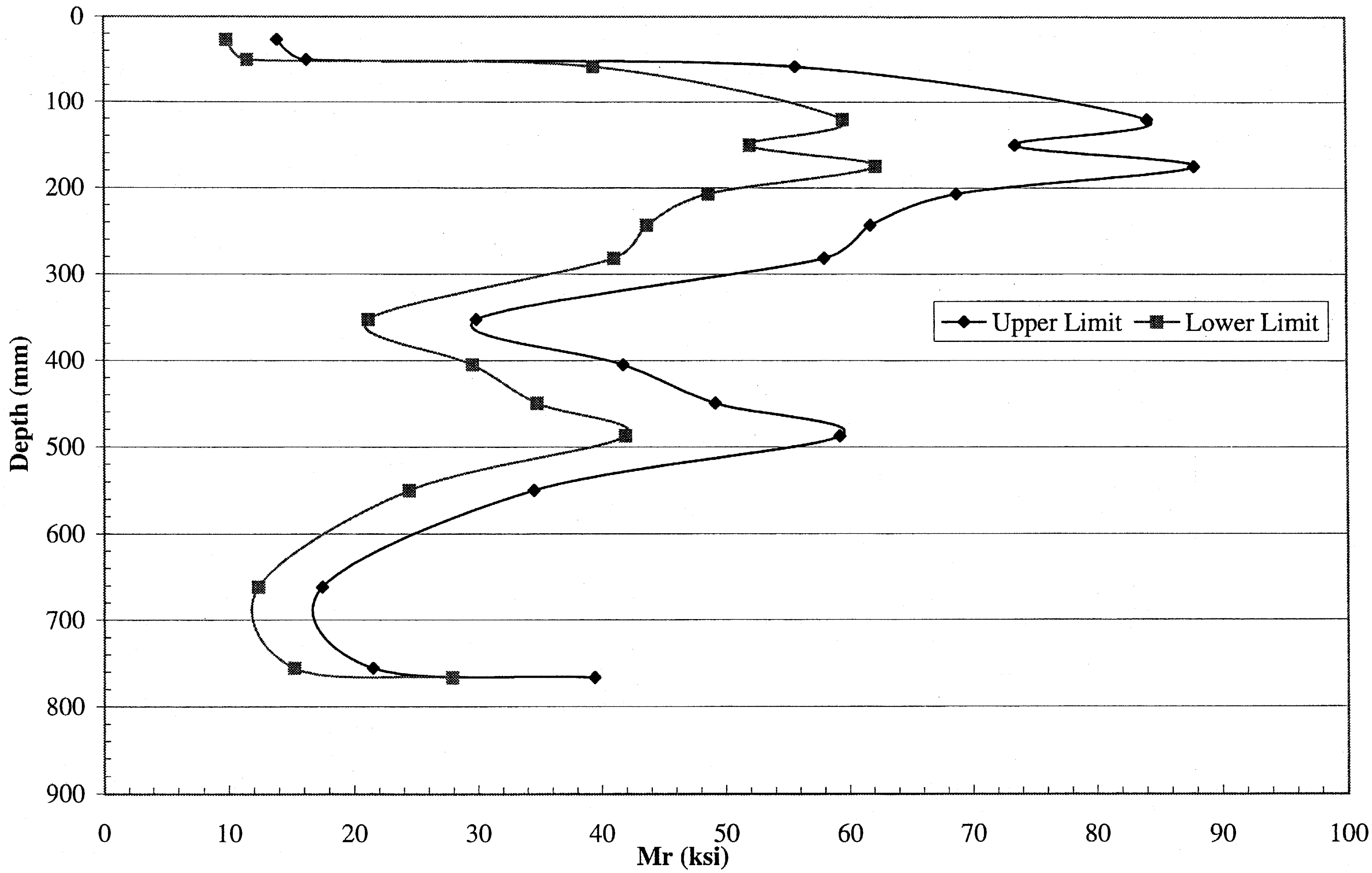

Figure D.29: Results of DCP Test on Subgrade at Station 424+00

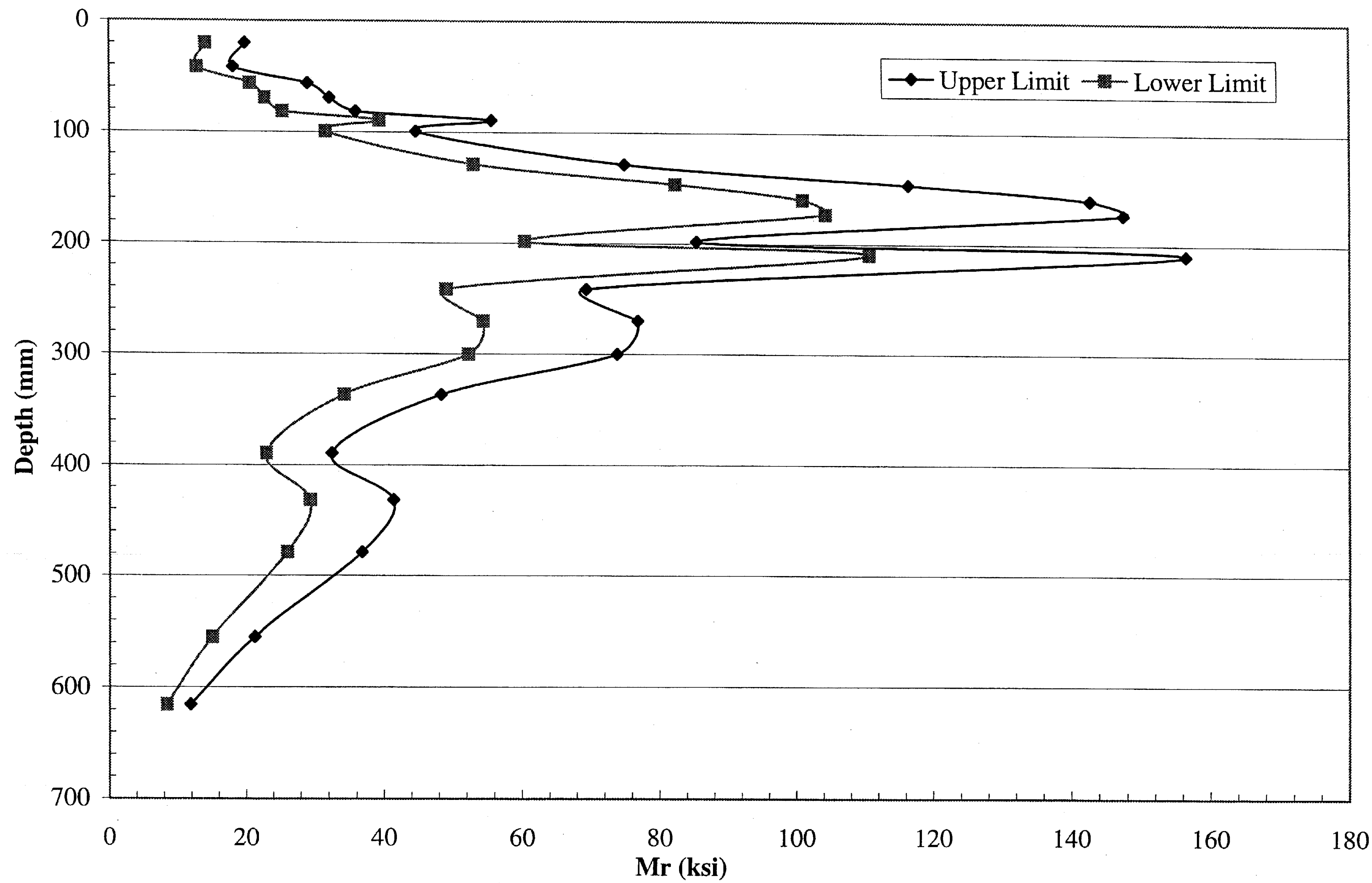

Figure D.30: Results of DCP Test on Subgrade at Station 424+50

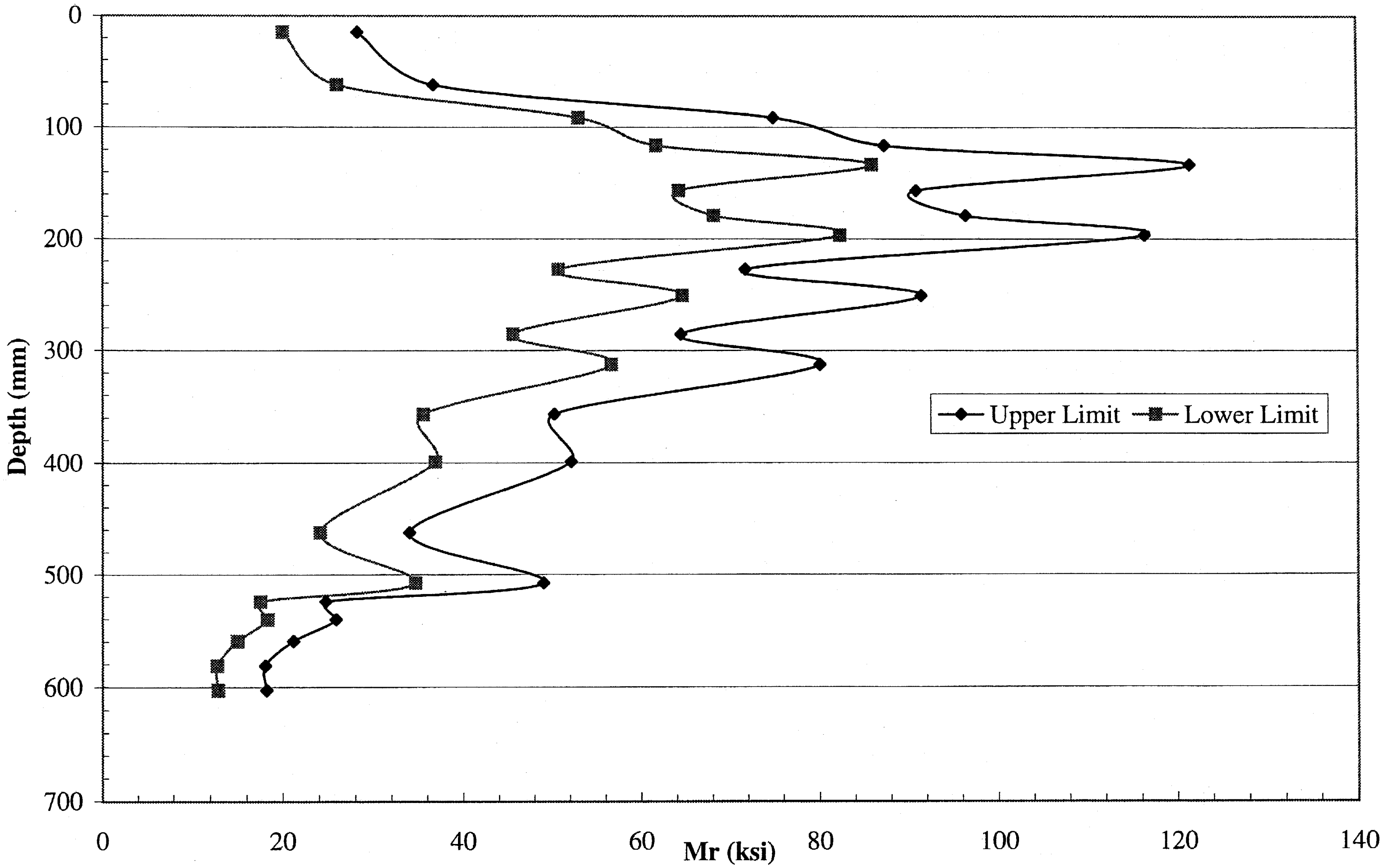

Figure D.31: Results of DCP Test on Subgrade at Station 425+00

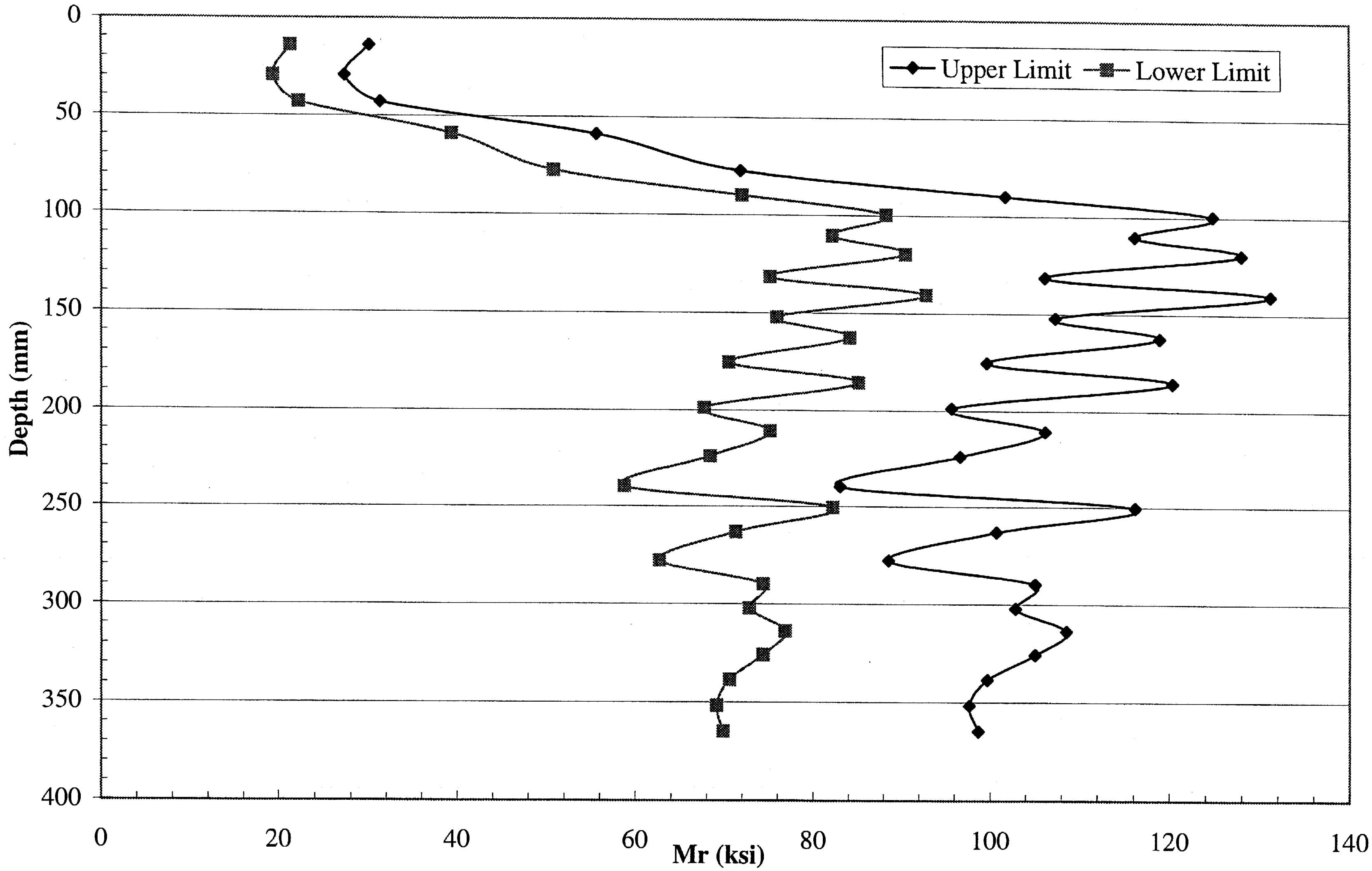

Figure D.32: Results of DCP Test on Subgrade at Station 425+50

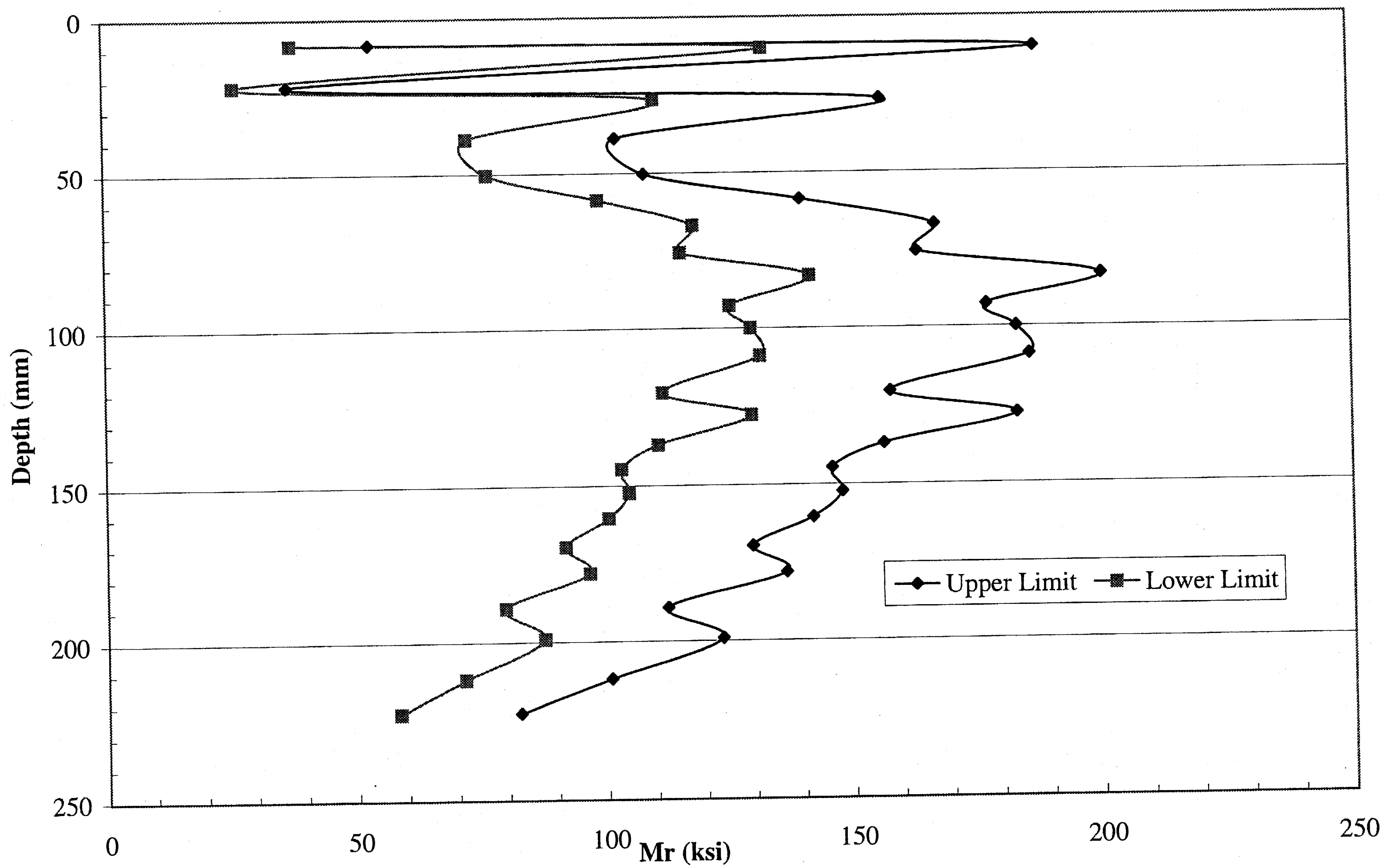

Figure D.33: Results of DCP Test on Subgrade at Station 426+00

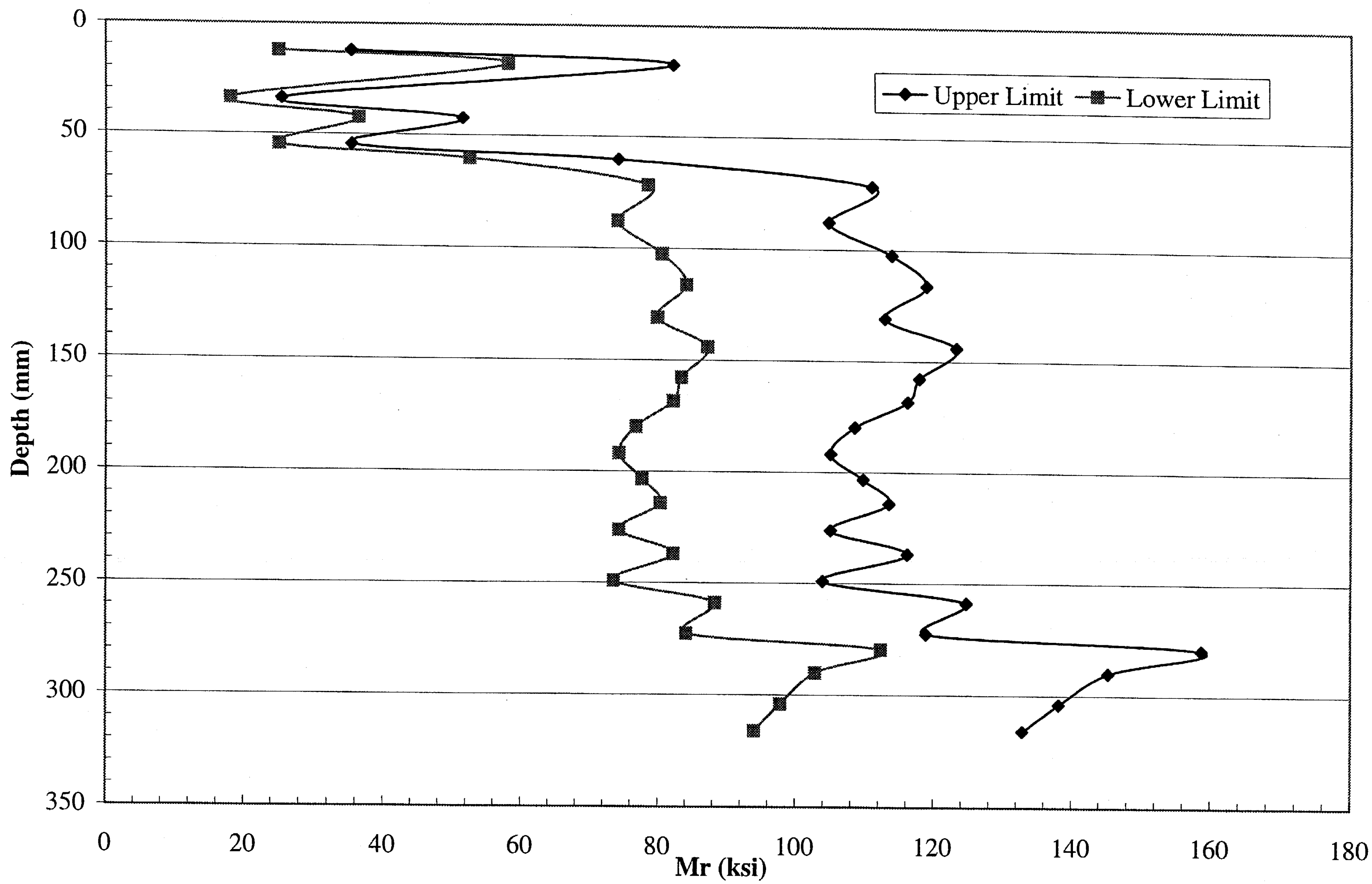

Figure D.34: Results of DCP Test on Subgrade at Station 426+50

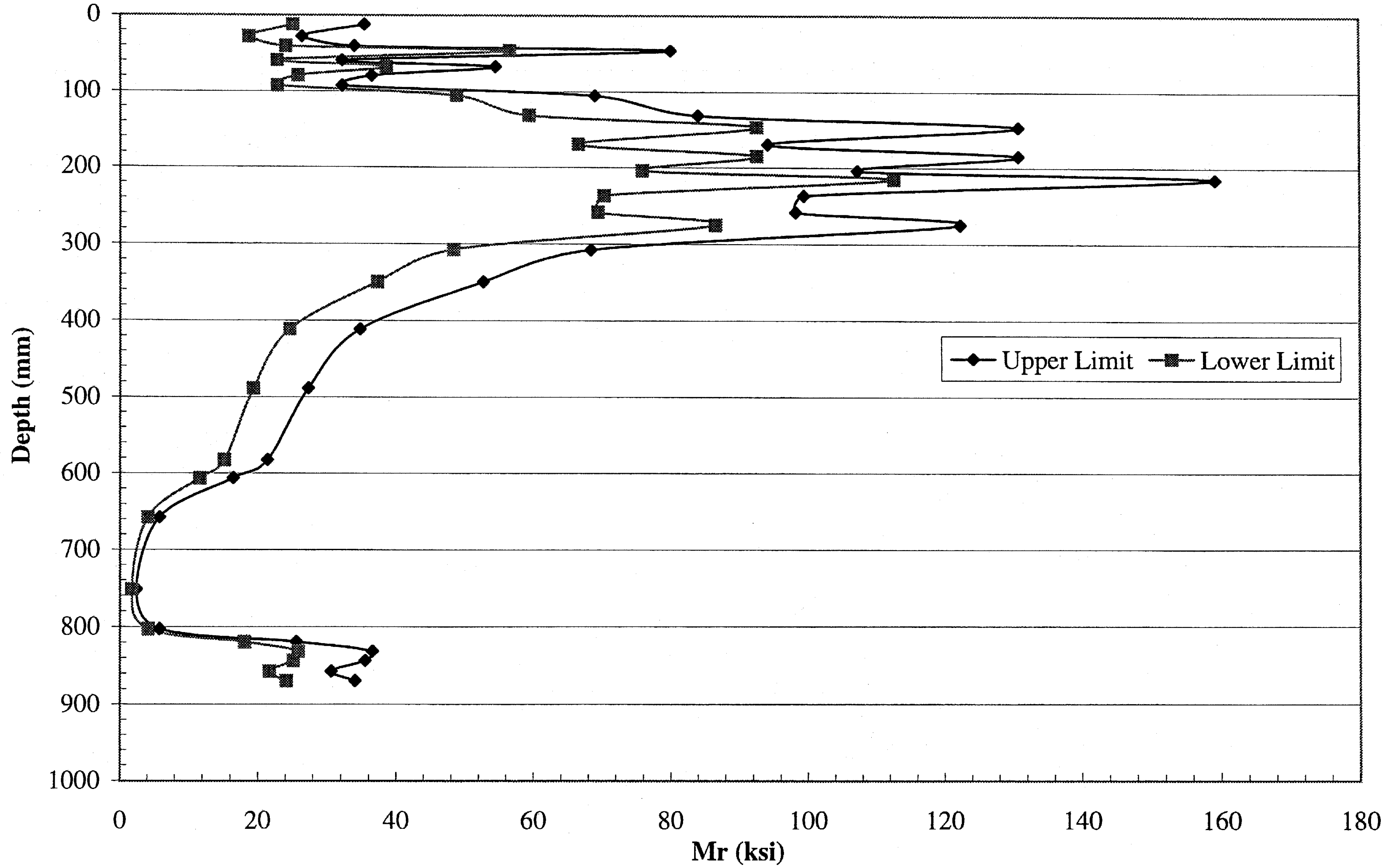

Figure D35: Results of DCP Test on Subgrade at Station 427+00

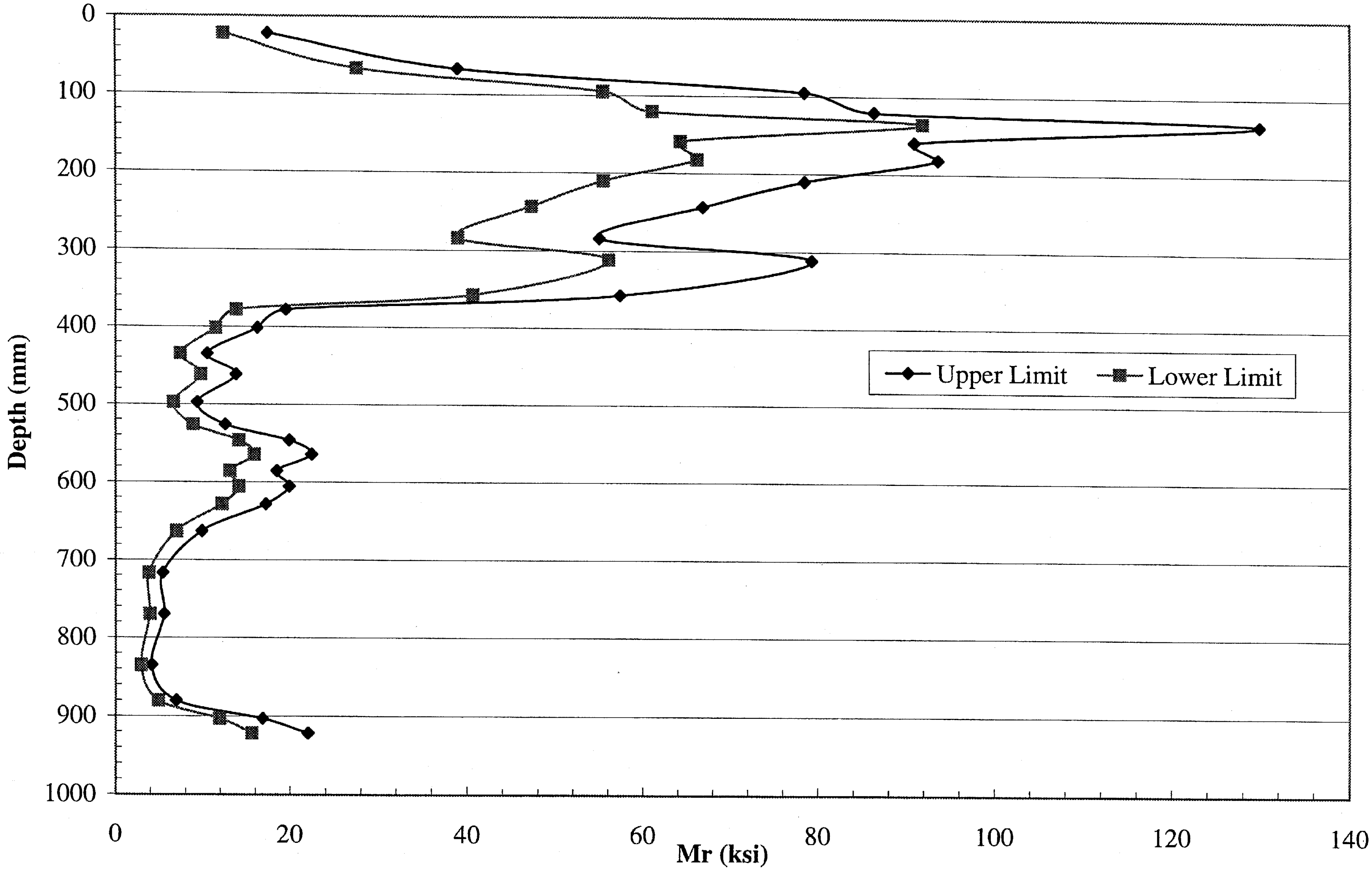

Figure D.36: Results of DCP Test on Subgrade at Station 427+50

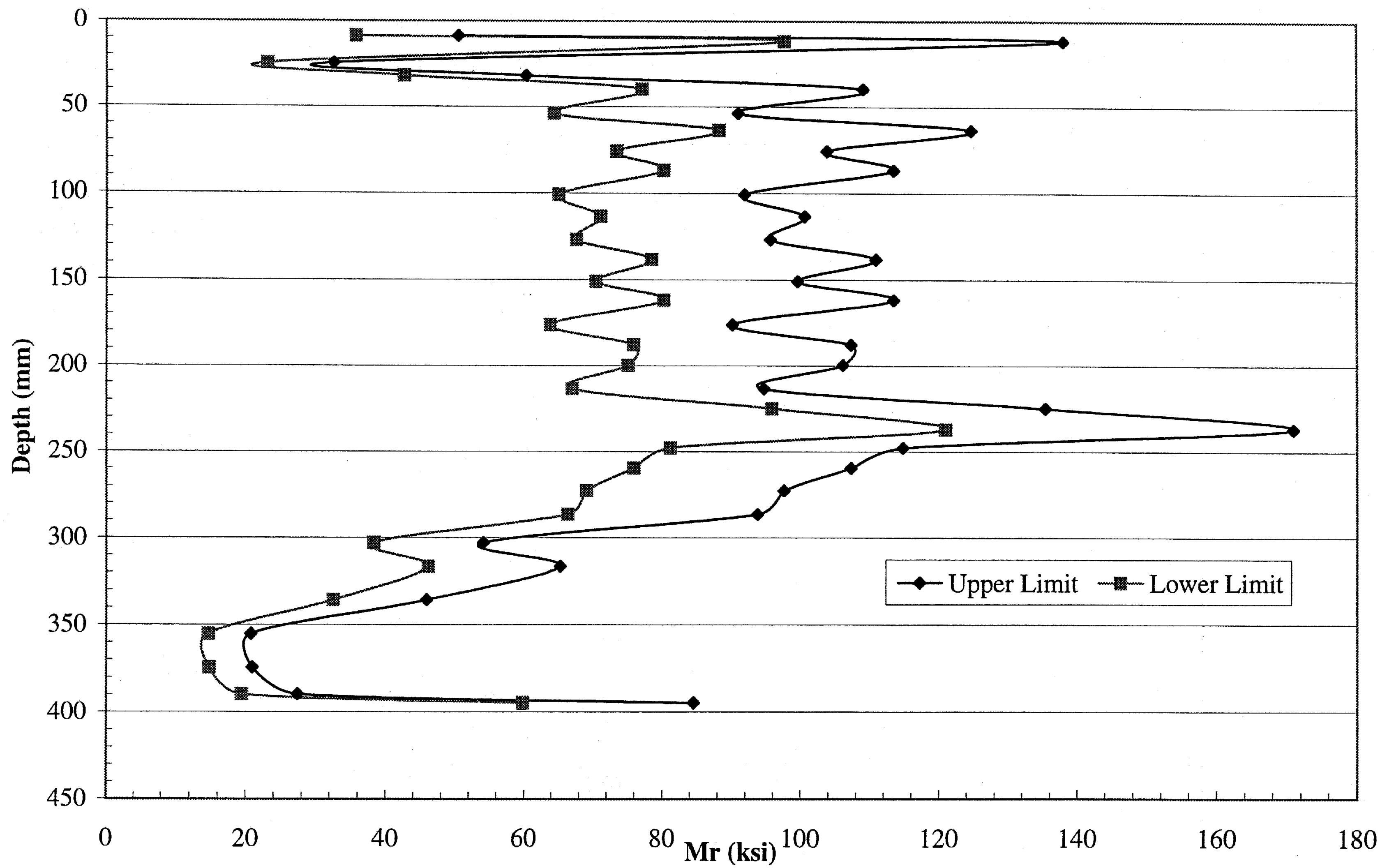

Figure D.37: Results of DCP Test on Subgrade at Station 428+00

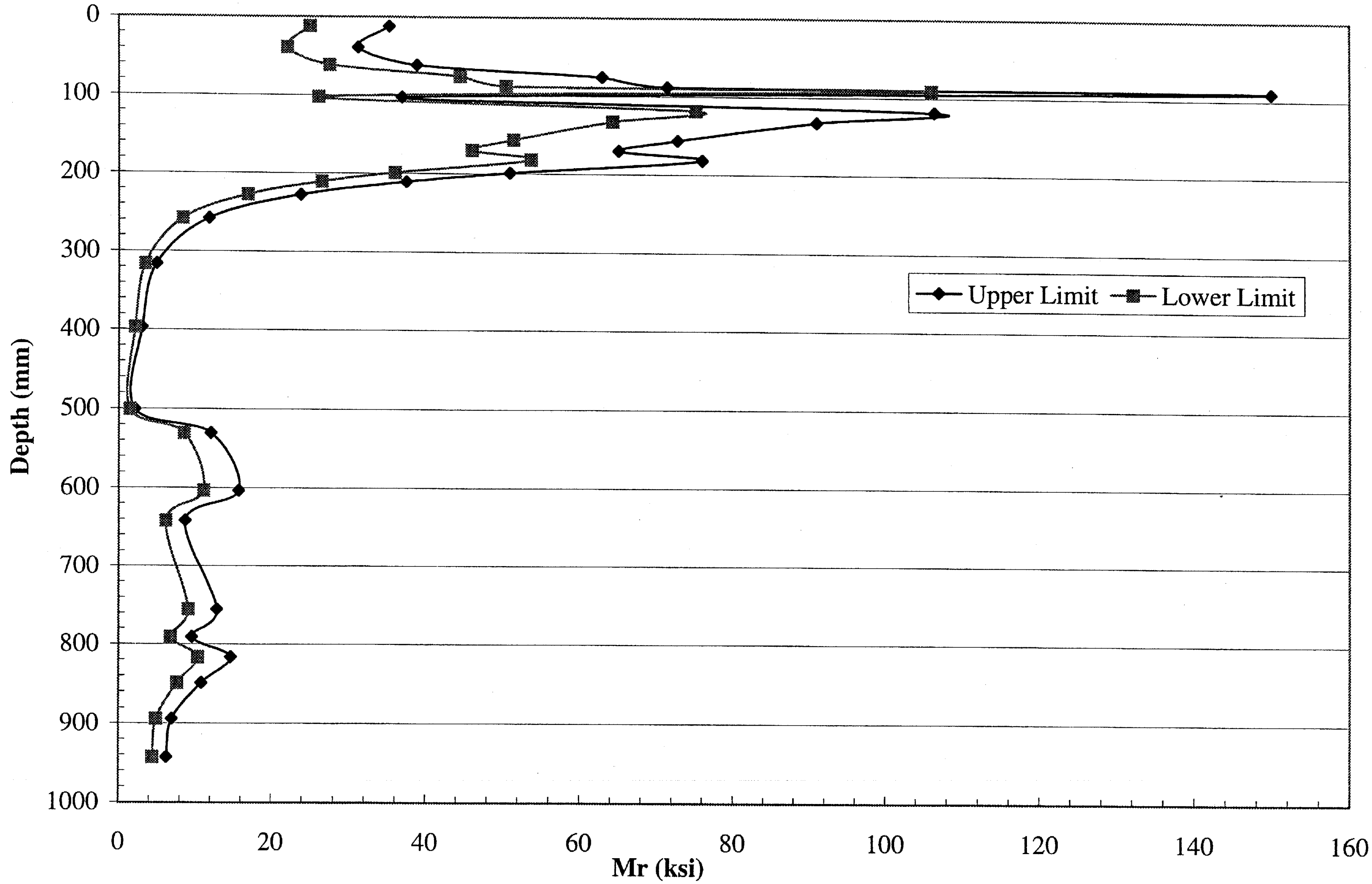

Figure D.38: Results of DCP Test on Subgrade at Station 428+50

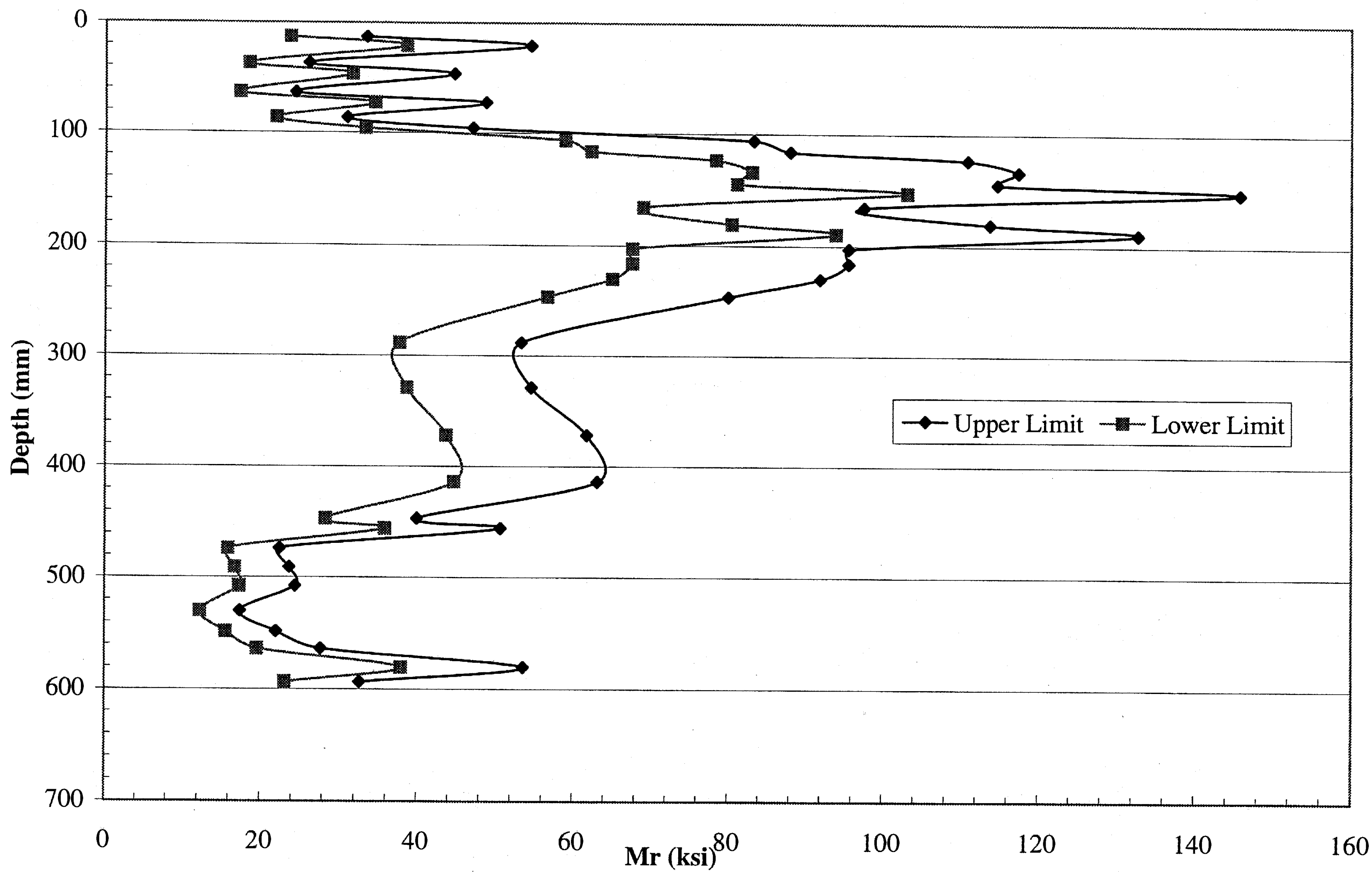

Figure D.39: Results of DCP Test on Subgrade at Station 429+00

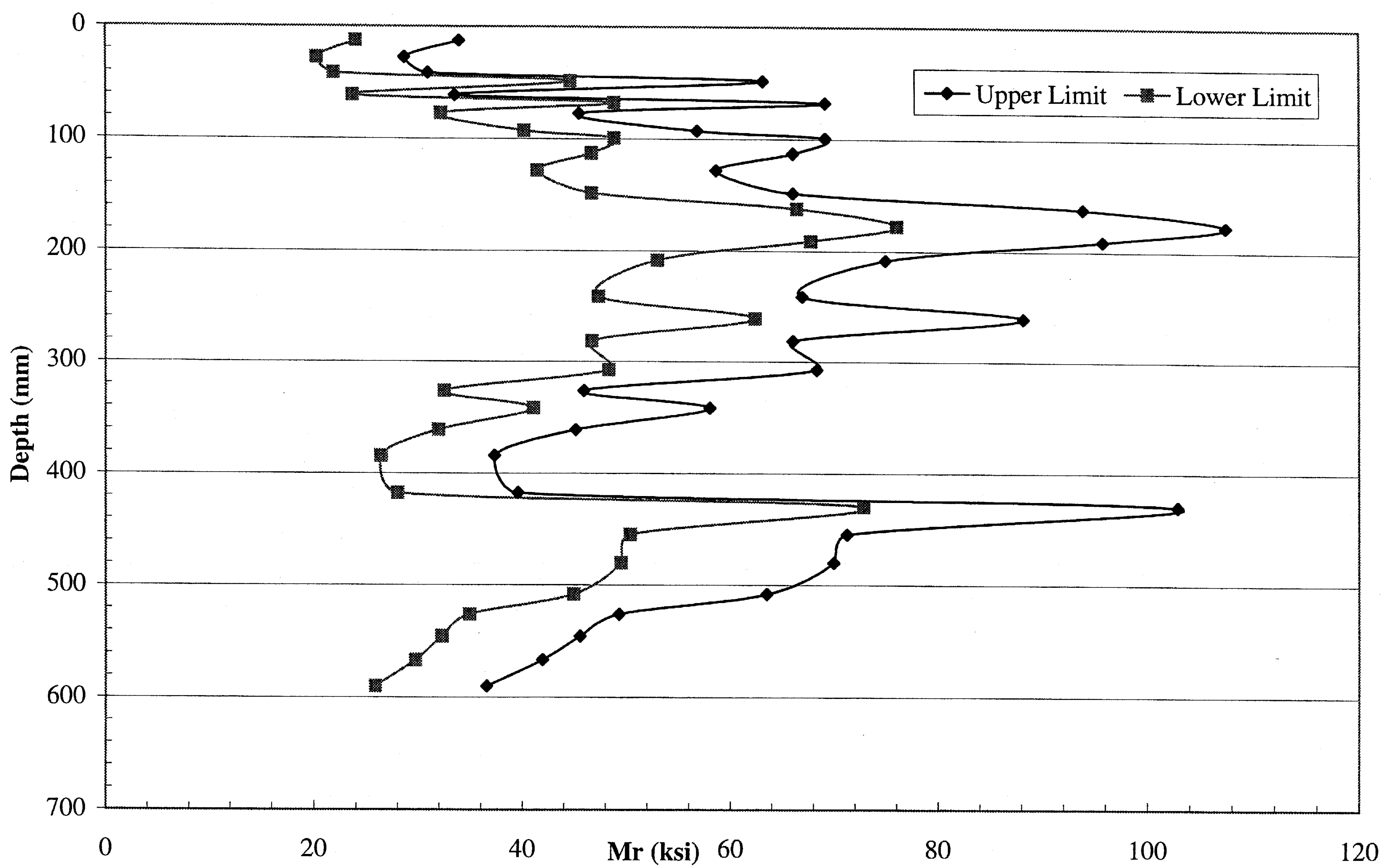

Figure D.40: Results of DCP Test on Subgrade at Station 429+50

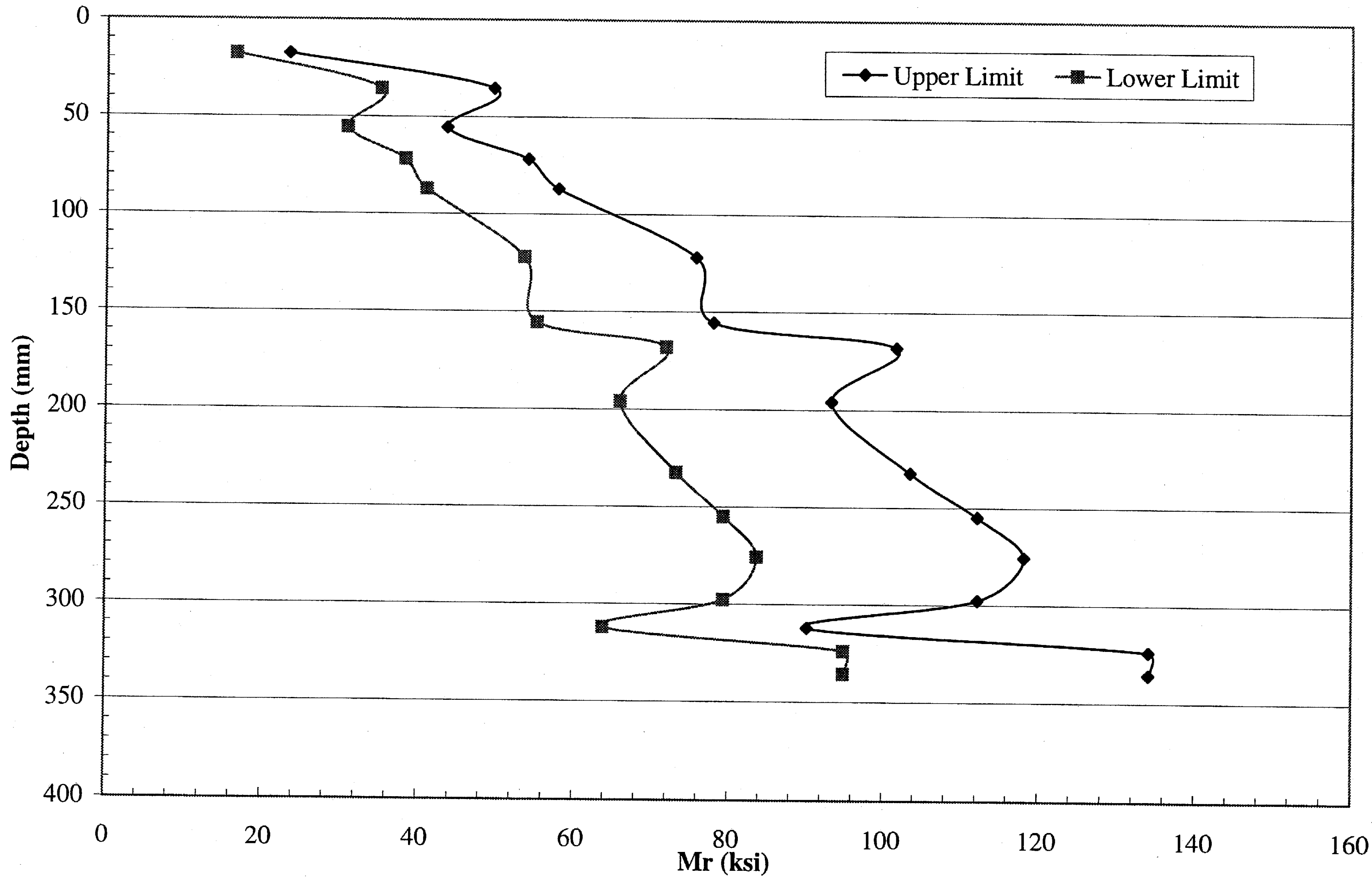

Figure D.41: Results of DCP Test on Subgrade at Station 430+00

APPENDIX E: Results of DCP Test on Base at each Station

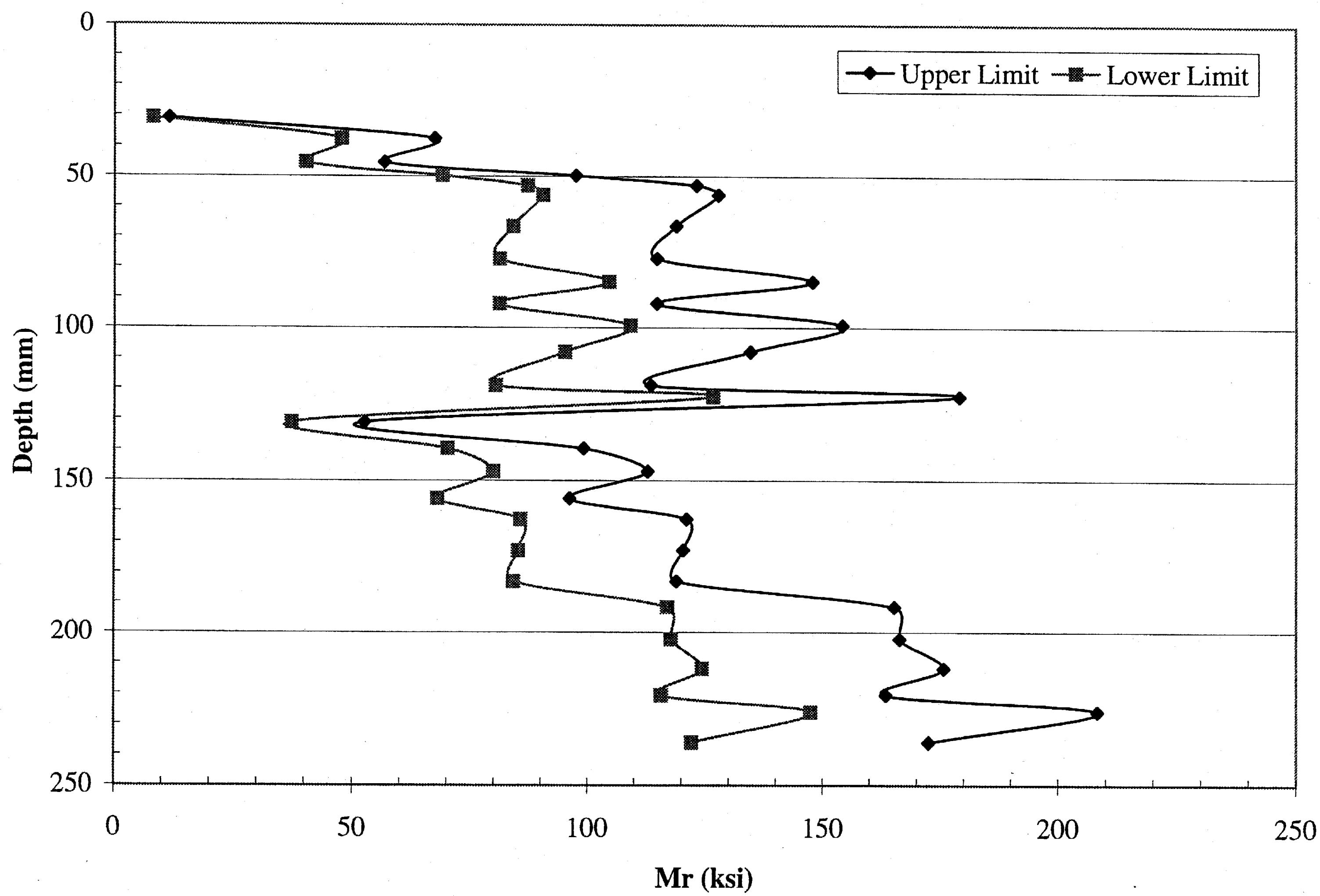

Figure E.1: Results of DCP Test on DGAB at Station 410+00

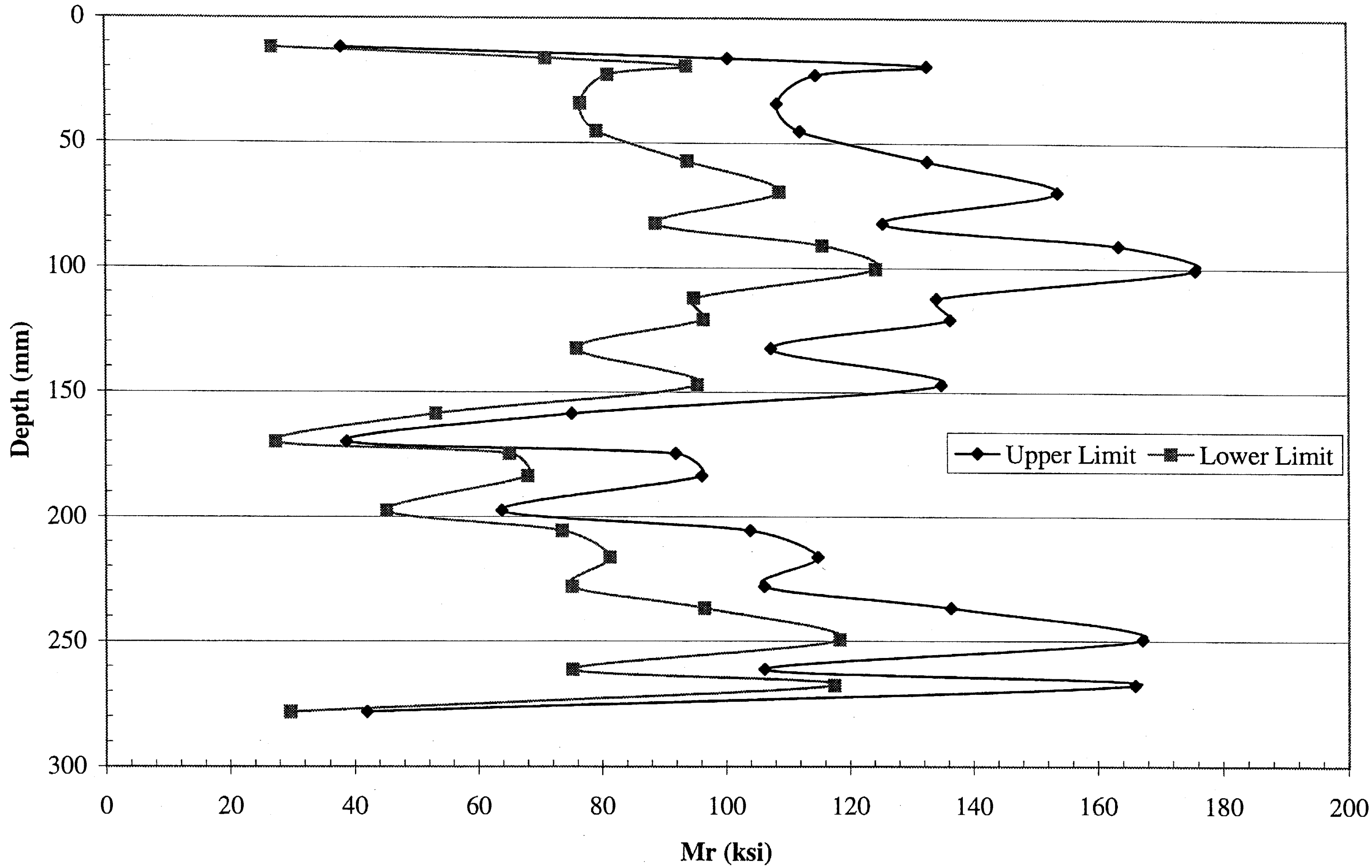

Figure E.2: Results of DCP Test on DGAB at Station 410+50

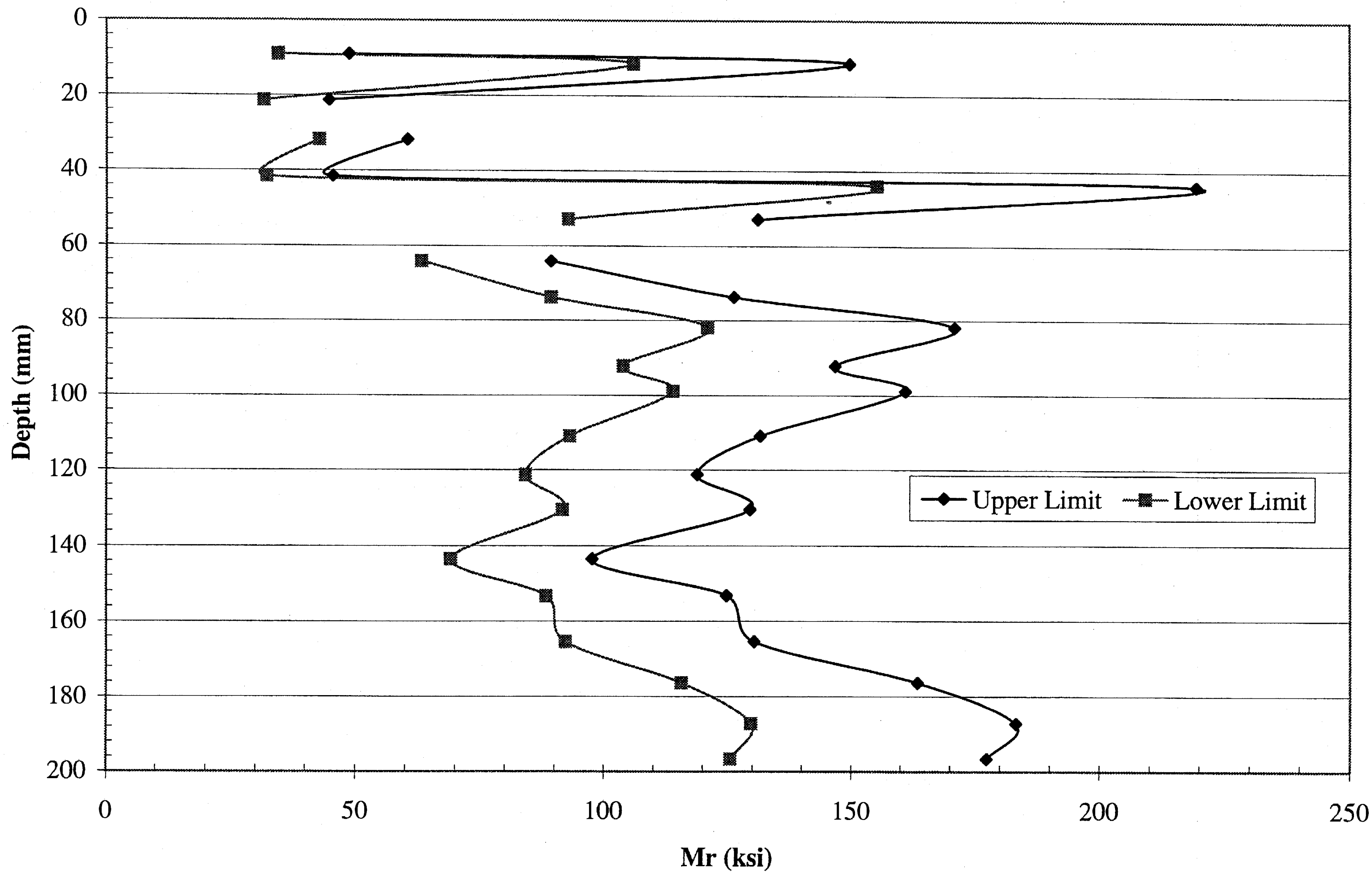

Figure E.3: Results of DCP Test on DGAB at Station 411+00

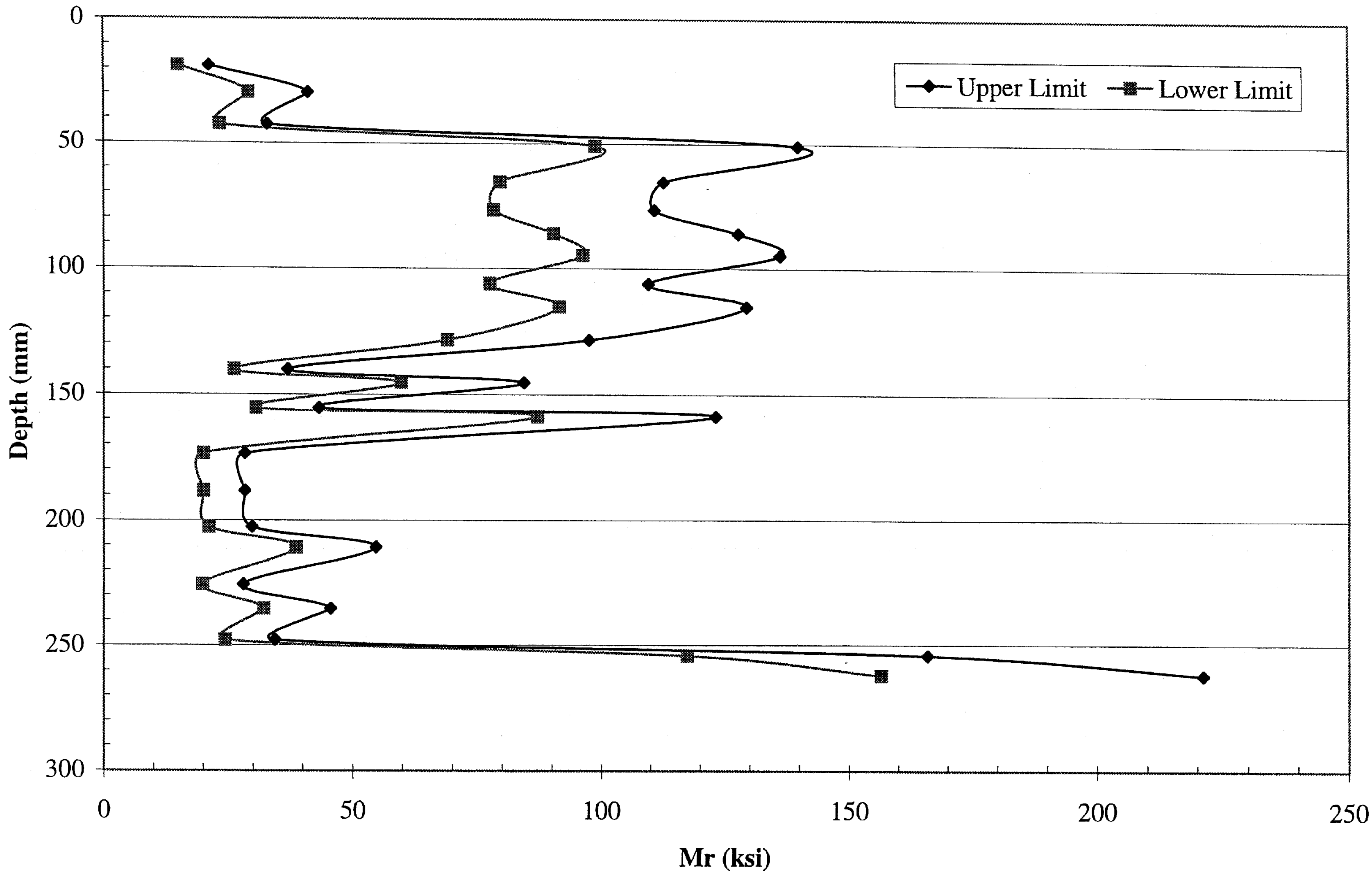

Figure E.4: Results of DCP Test on DGAB at Station 411+50

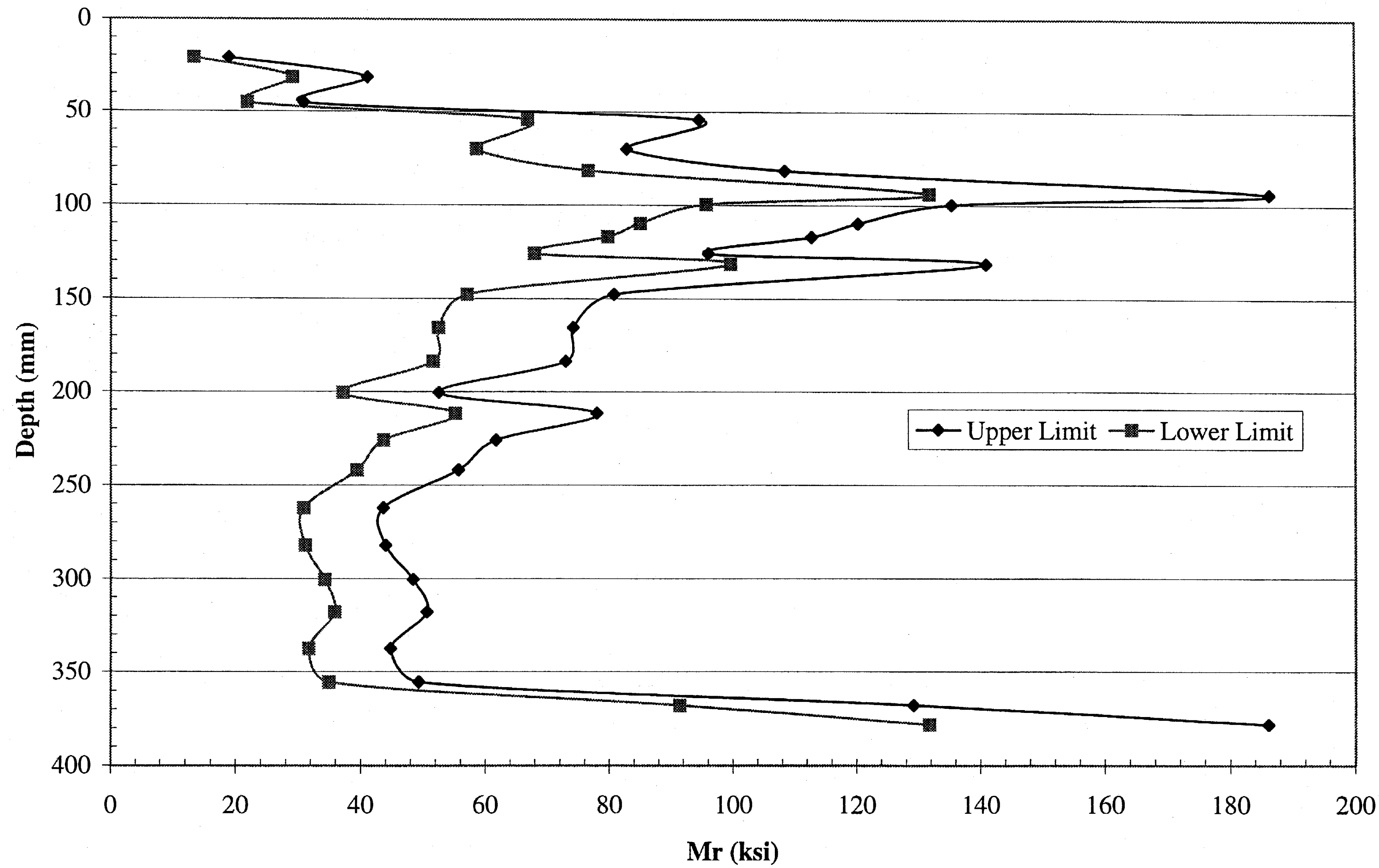

Figure E.5: Results of DCP Test on DGAB at Station 412+00

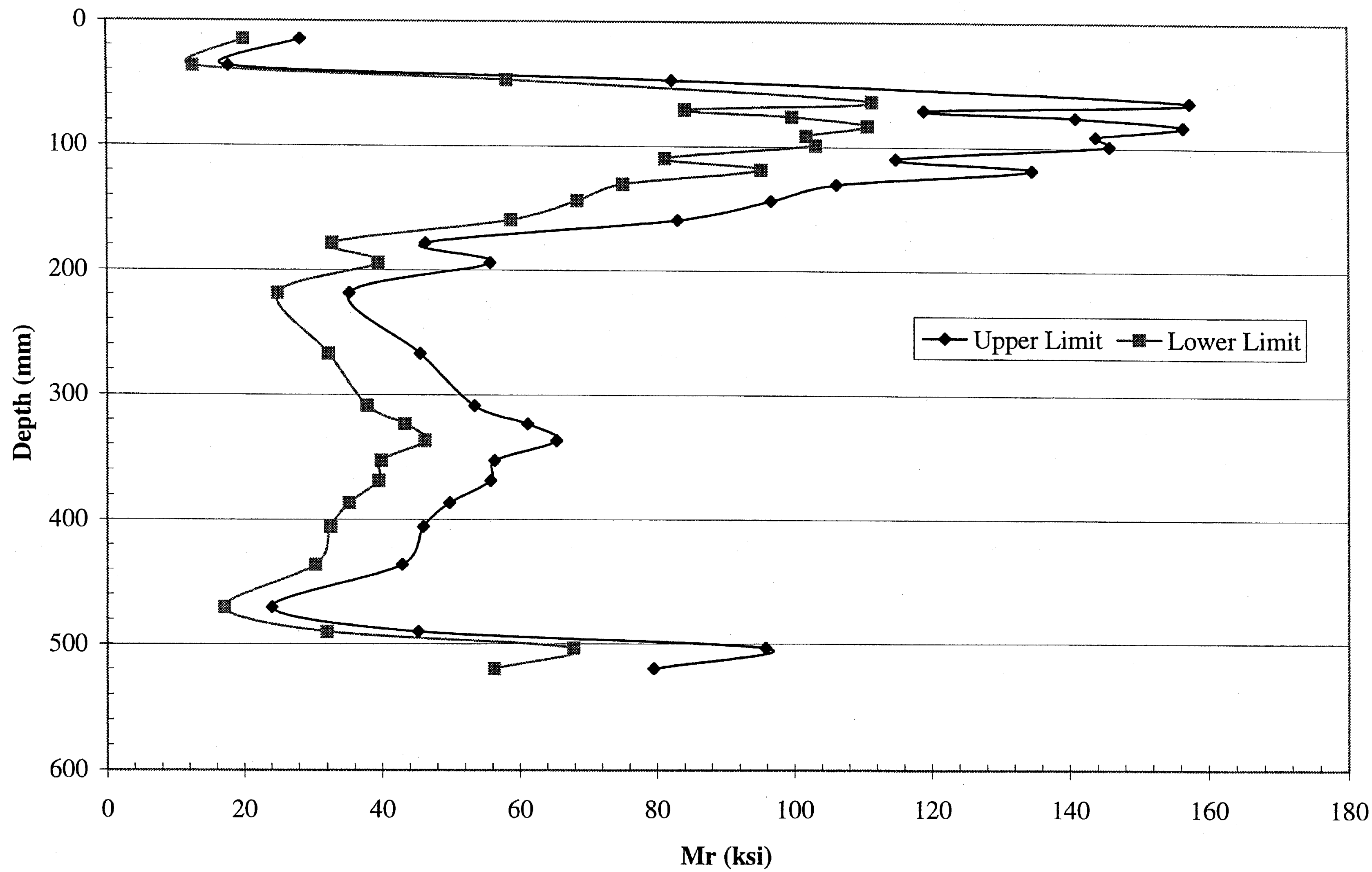

Figure E.6: Results of DCP Test on DGAB at Station 412+50

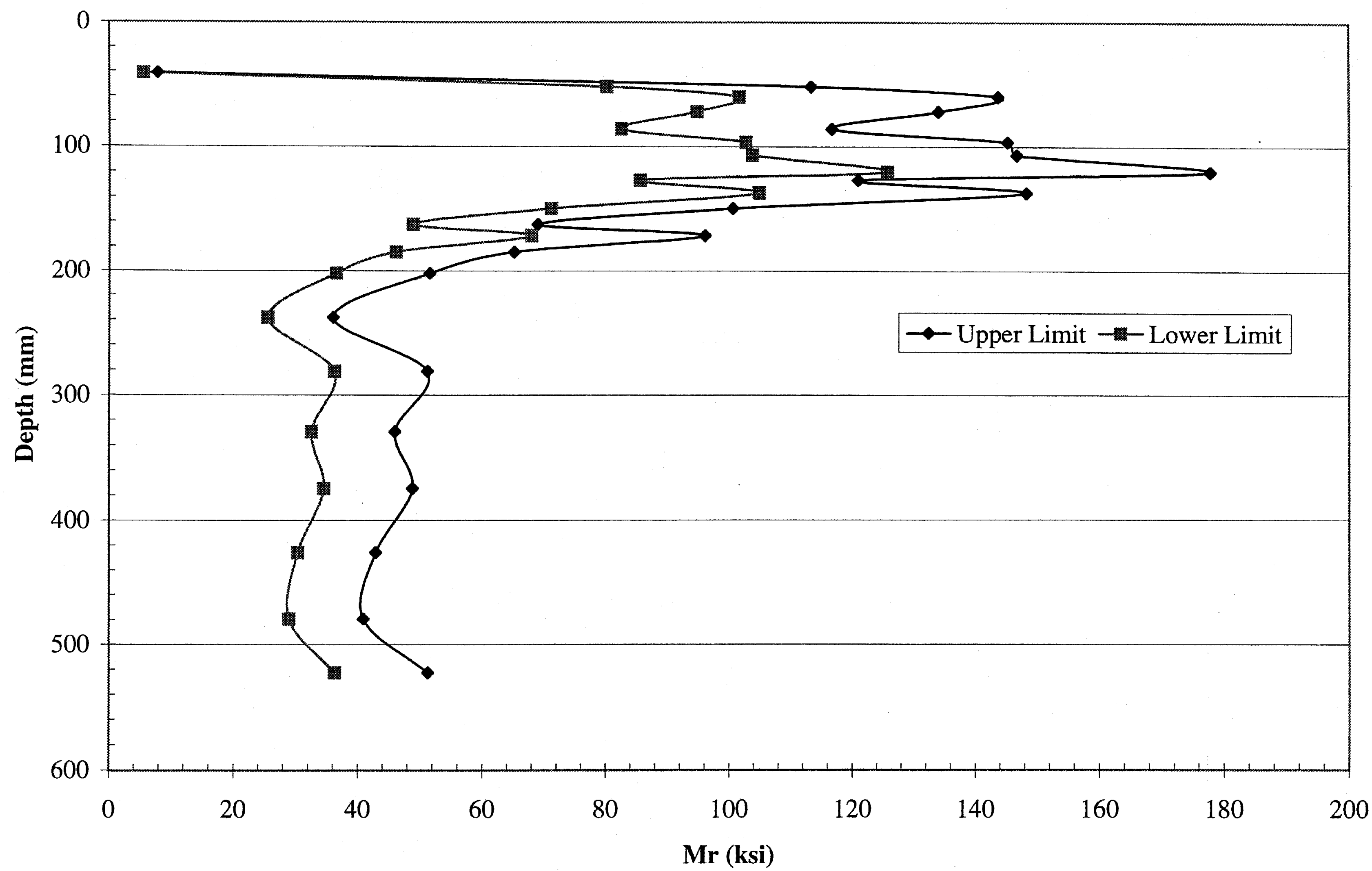

Figure E.7: Results of DCP Test on DGAB at Station 413+00

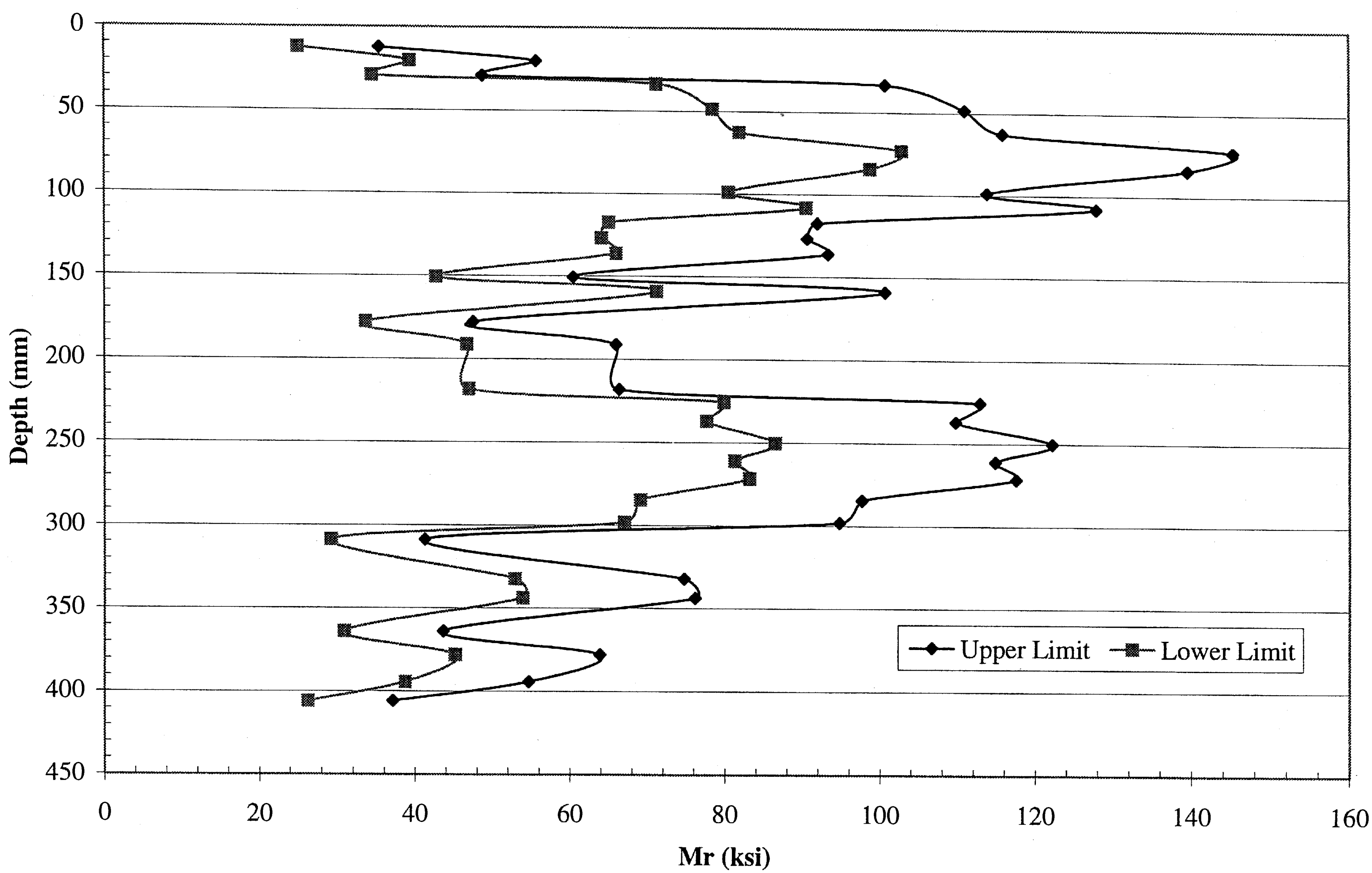

Figure E.8: Results of DCP Test on DGAB at Station 413+50

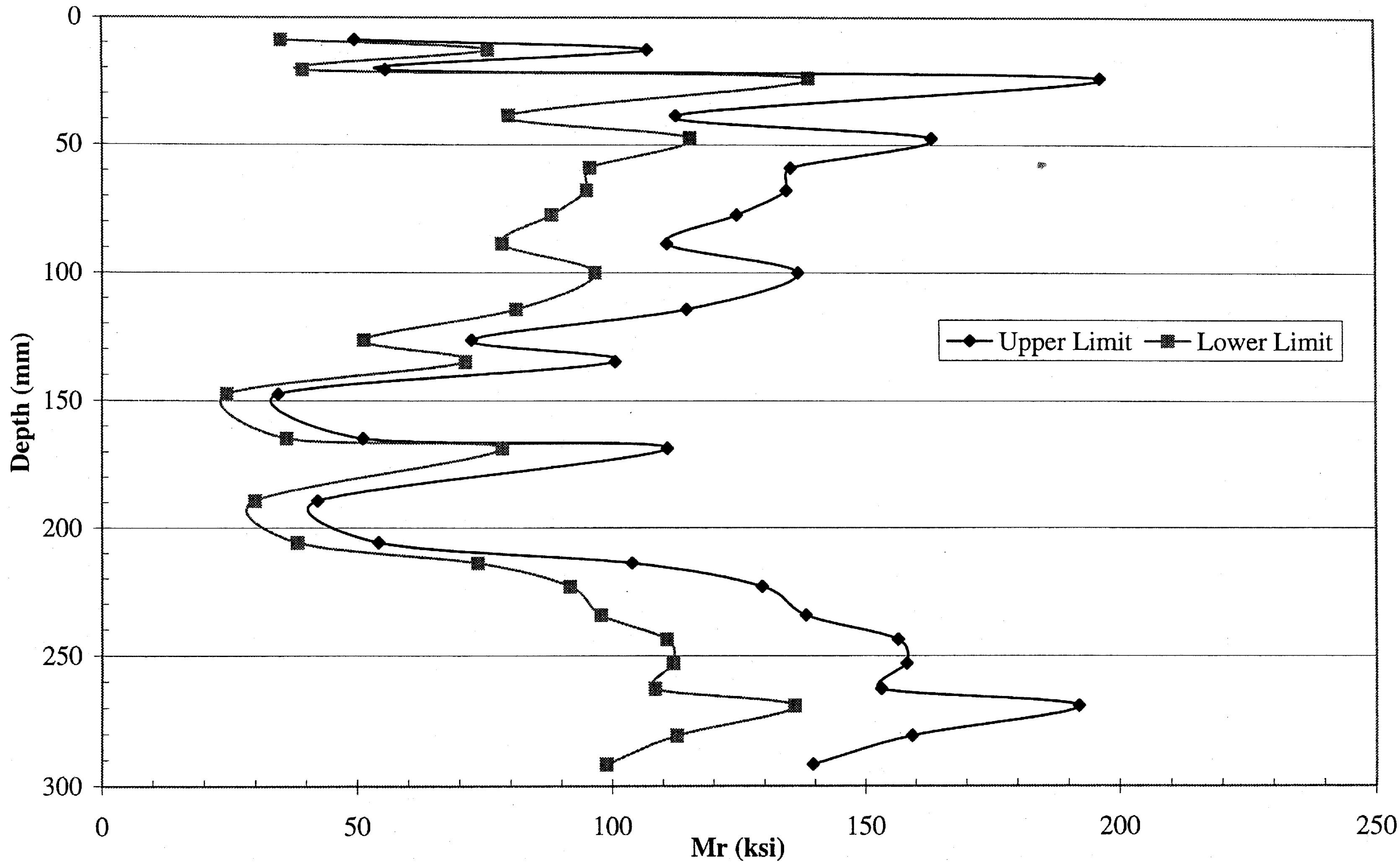

Figure E.9: Results of DCP Test on DGAB at Station 414+00

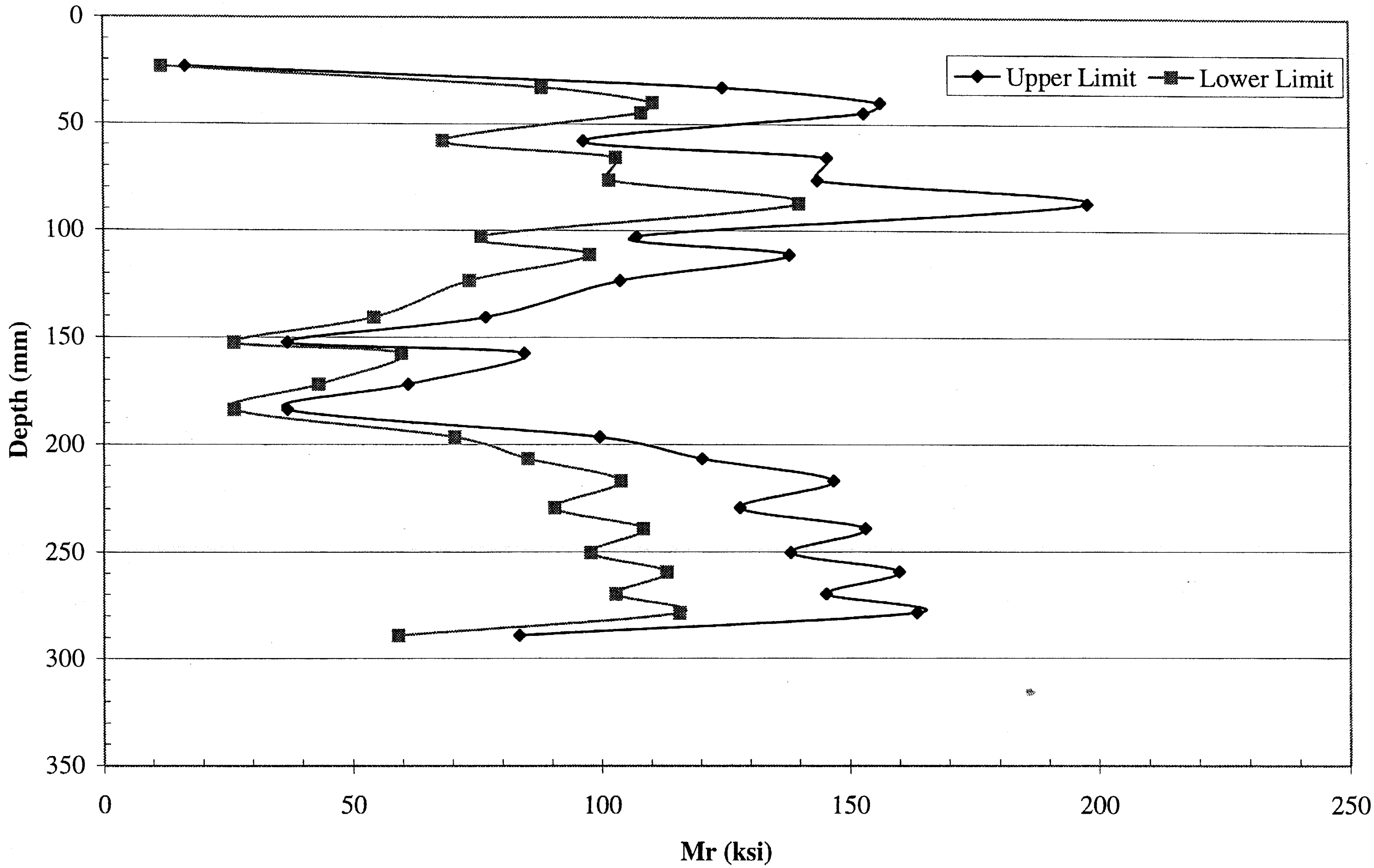

Figure E.10: Results of DCP Test on DGAB at Station 414+50

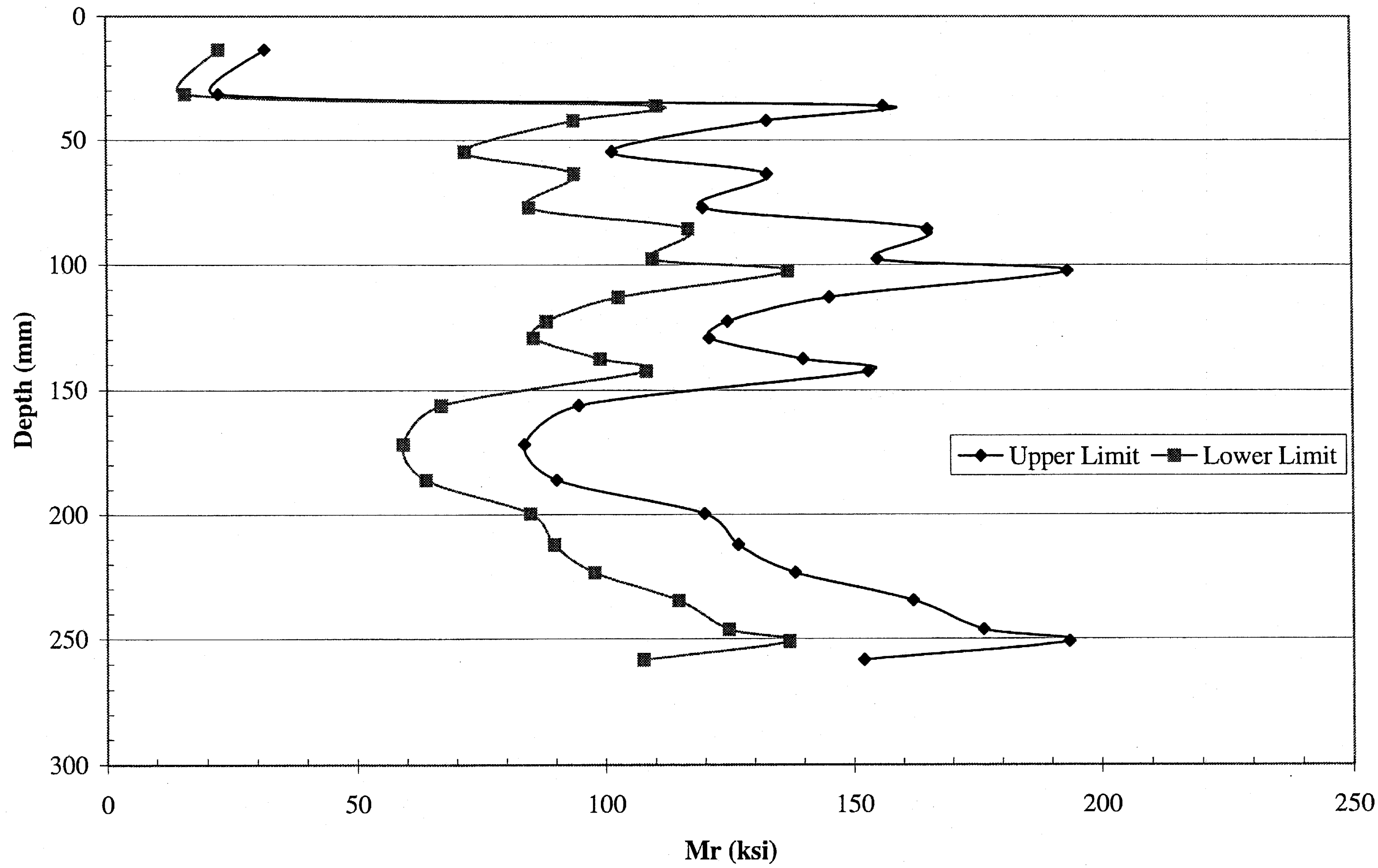

Figure E.11: Results of DCP Test on DGAB at Station 415+00

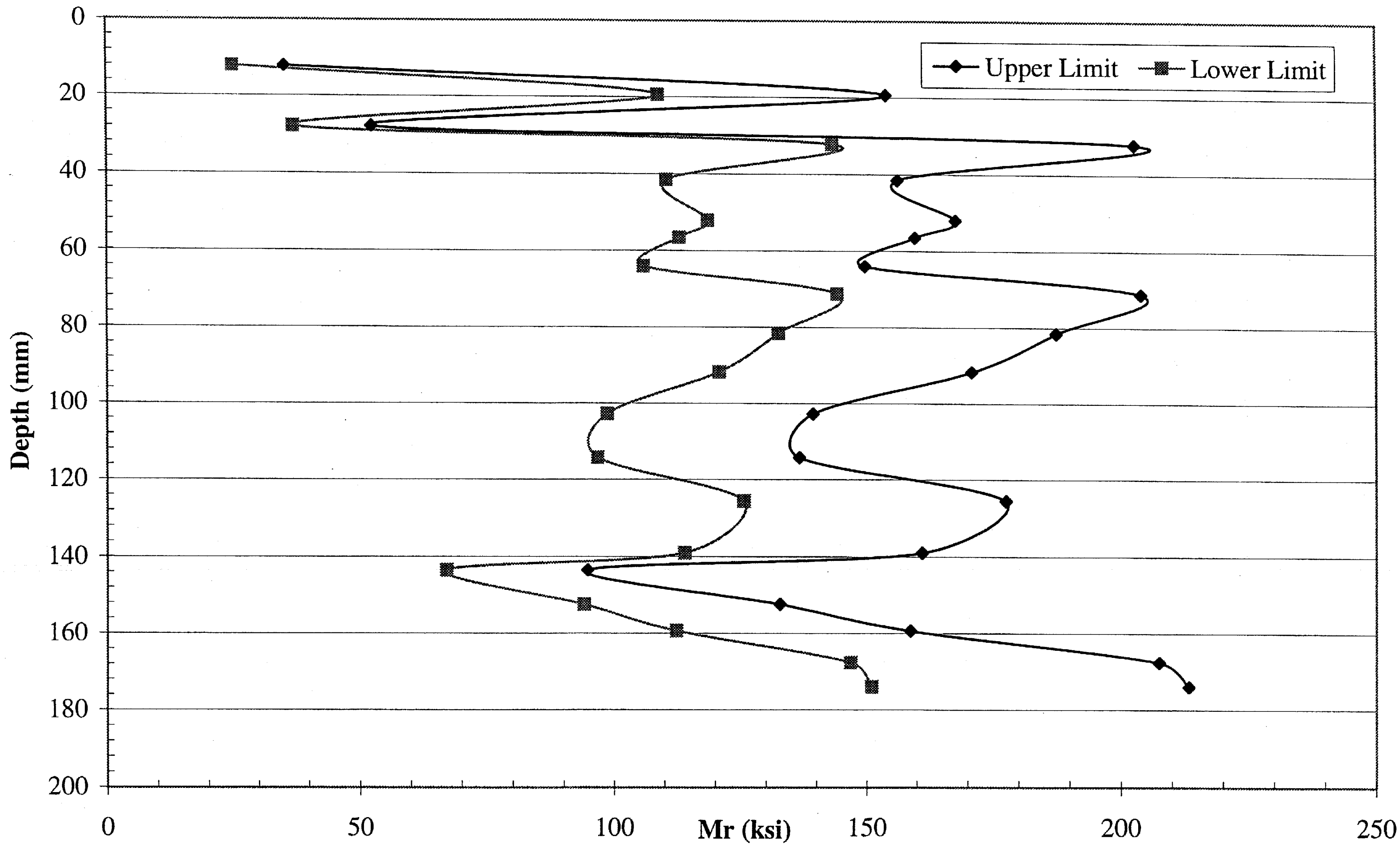

Figure E.12: Results of DCP Test on DGAB at Station 415+50

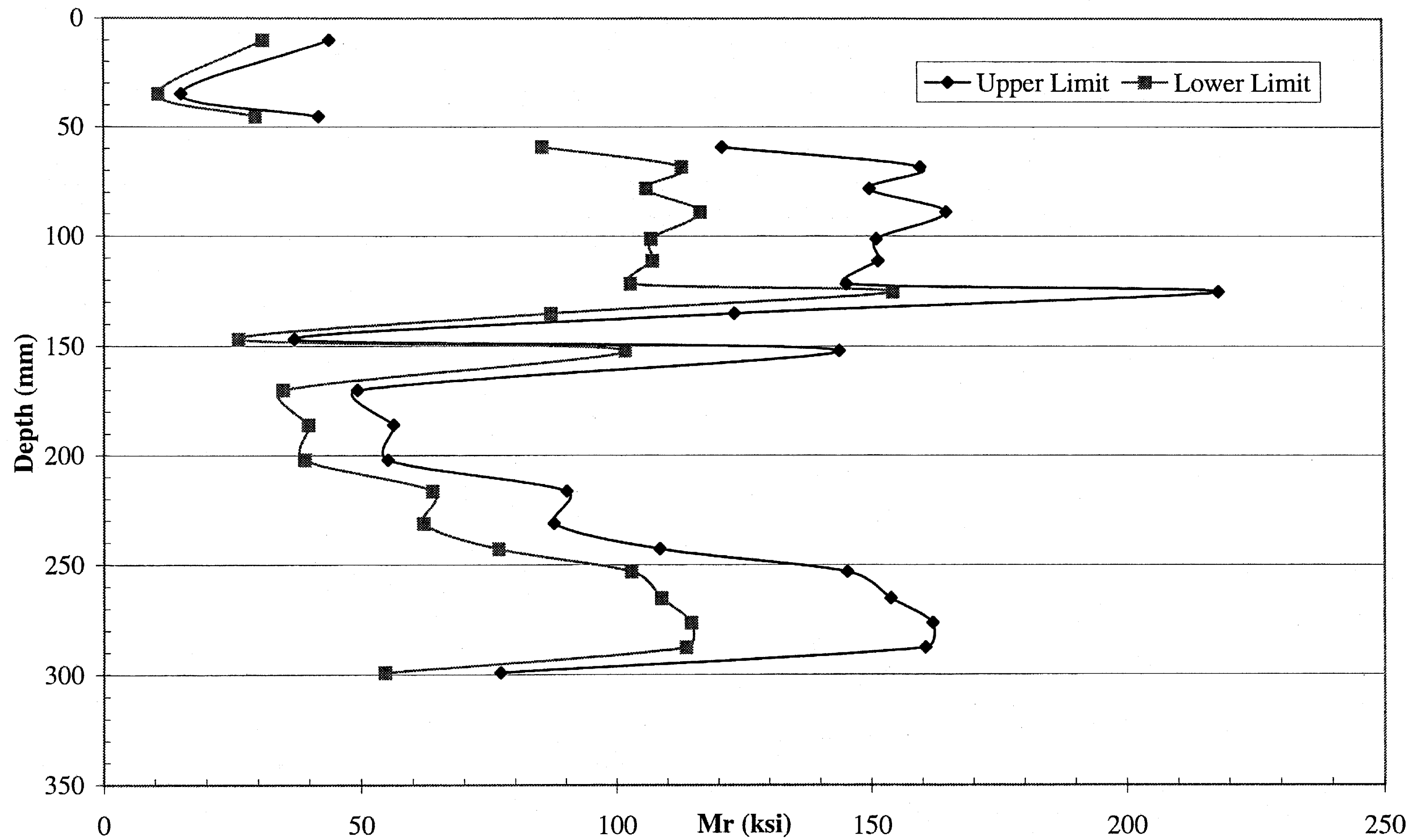

Figure E.13: Results of DCP Test on DGAB at Station 416+00

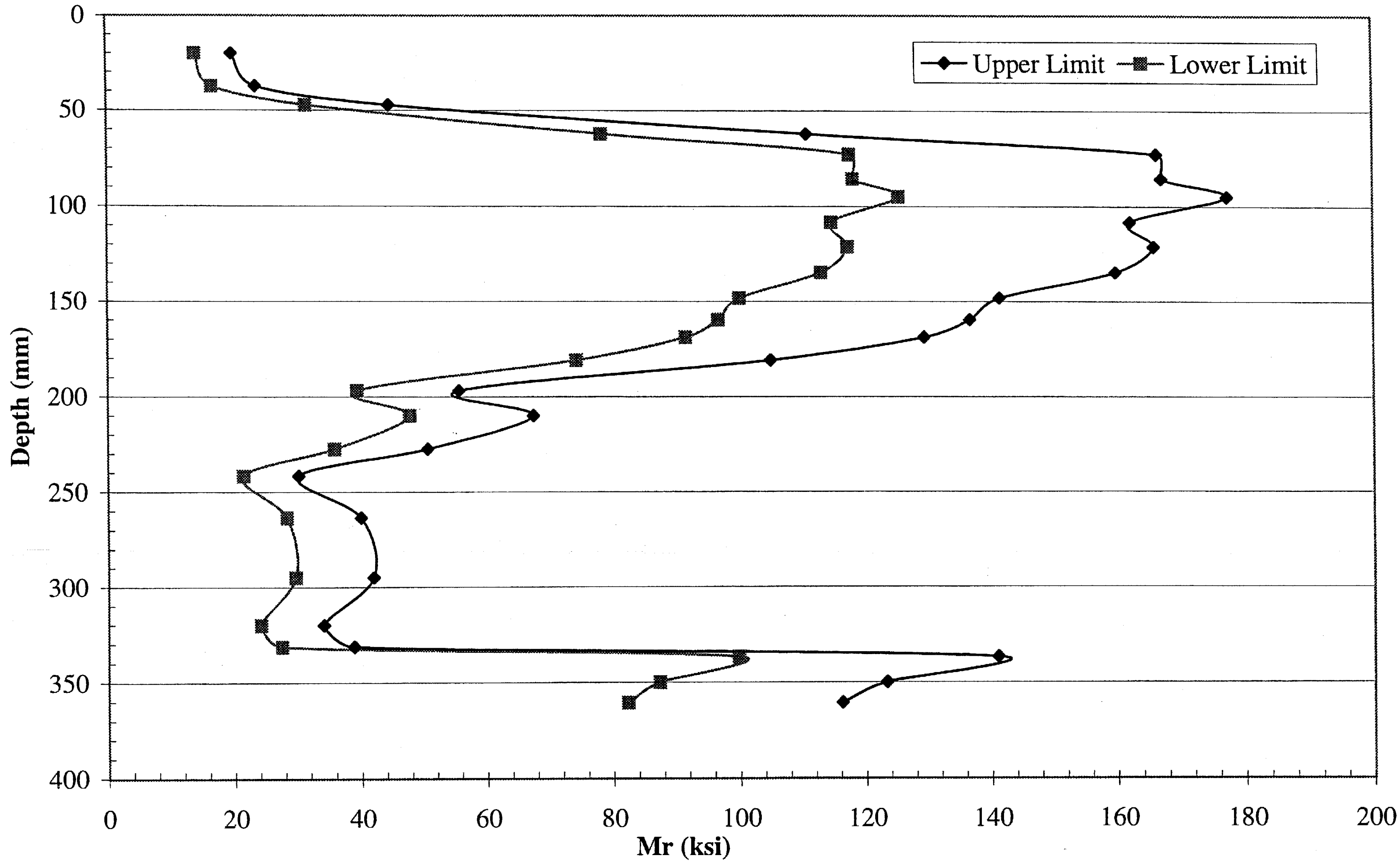

Figure E.14: Results of DCP Test on DGAB at Station 416+50

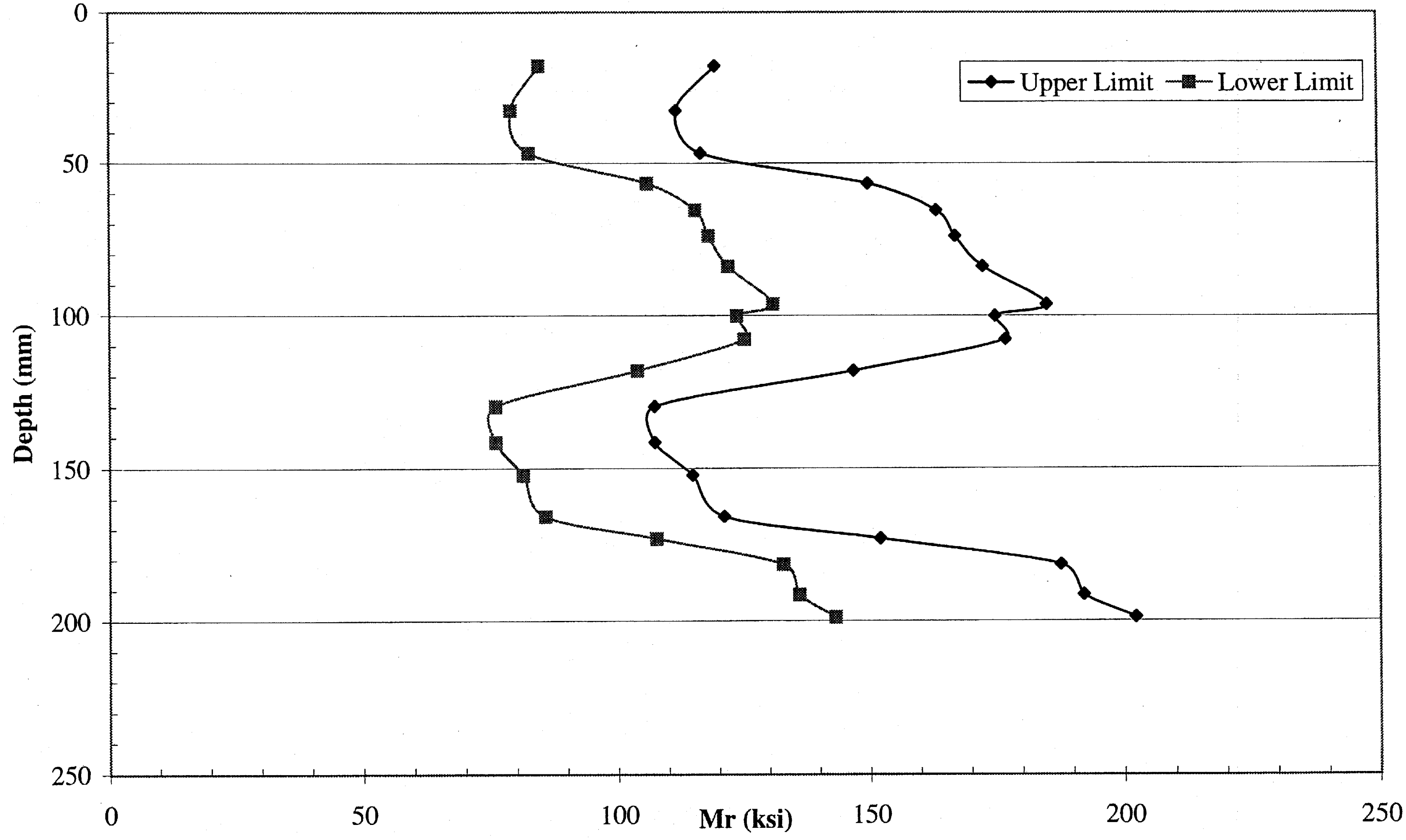

Figure E.15: Results of DCP Test on DGAB at Station 417+00

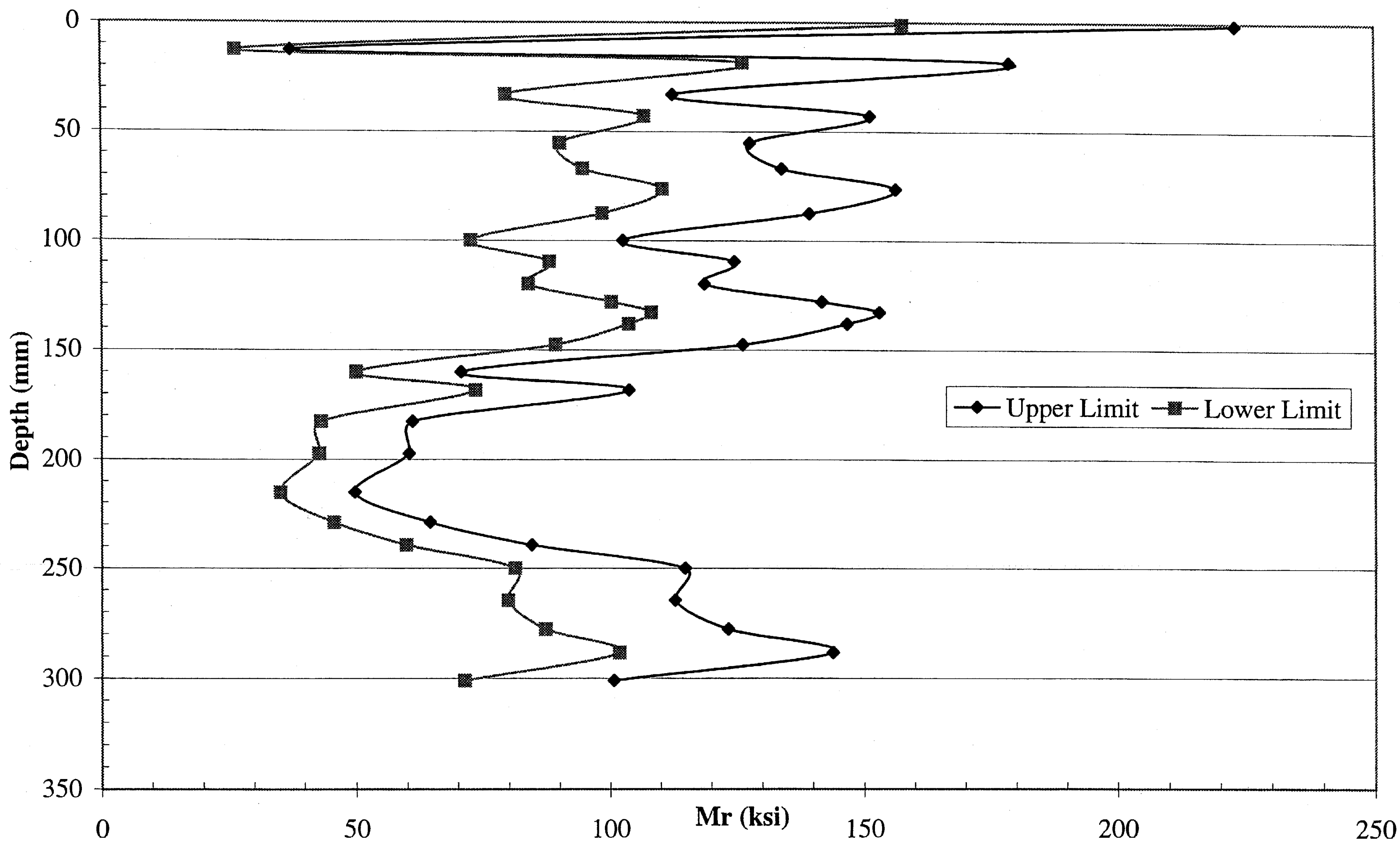

Figure E.16: Results of DCP Test on DGAB at Station 417+50

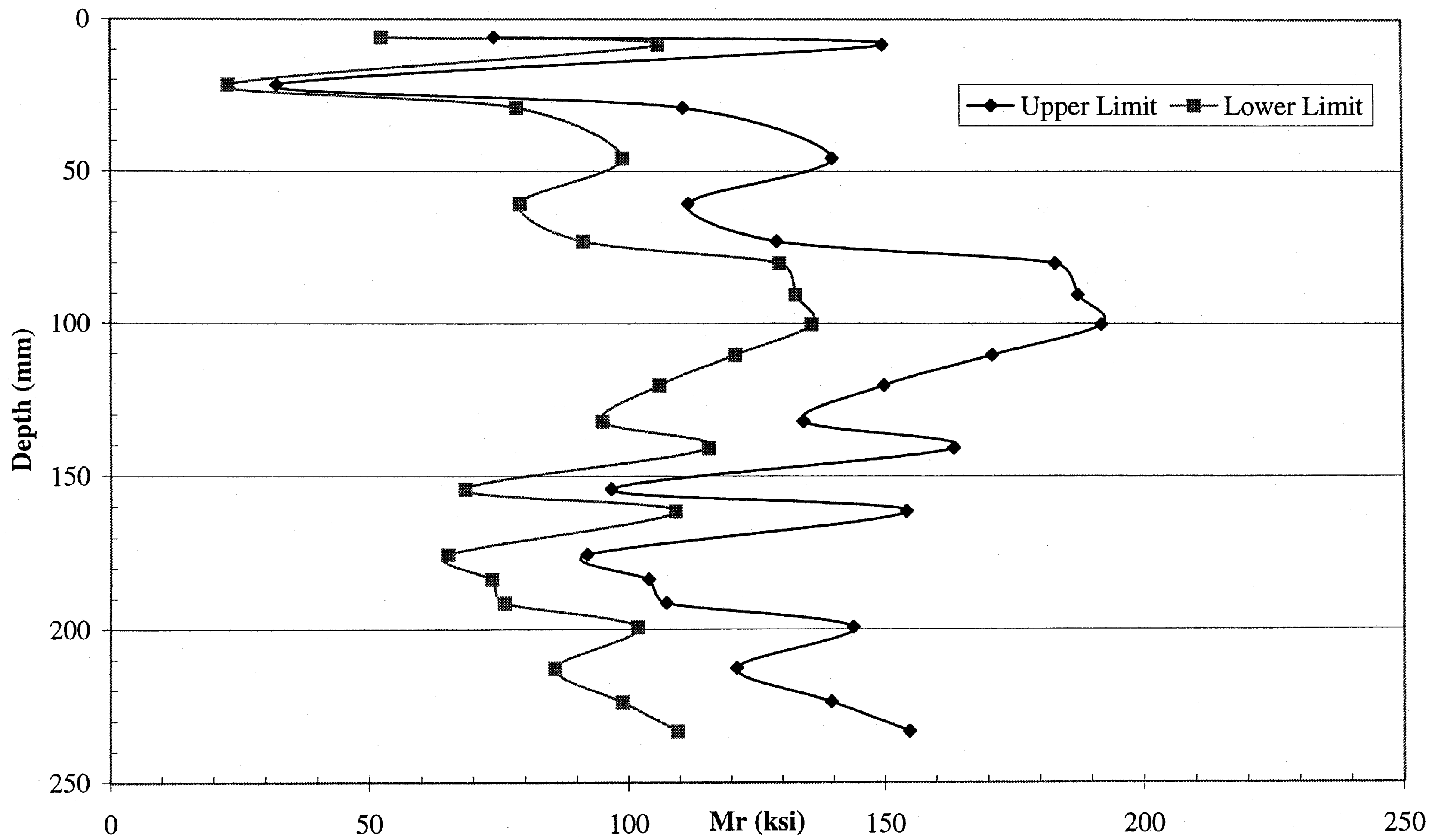

Figure E.17: Results of DCP Test on DGAB at Station 418+00

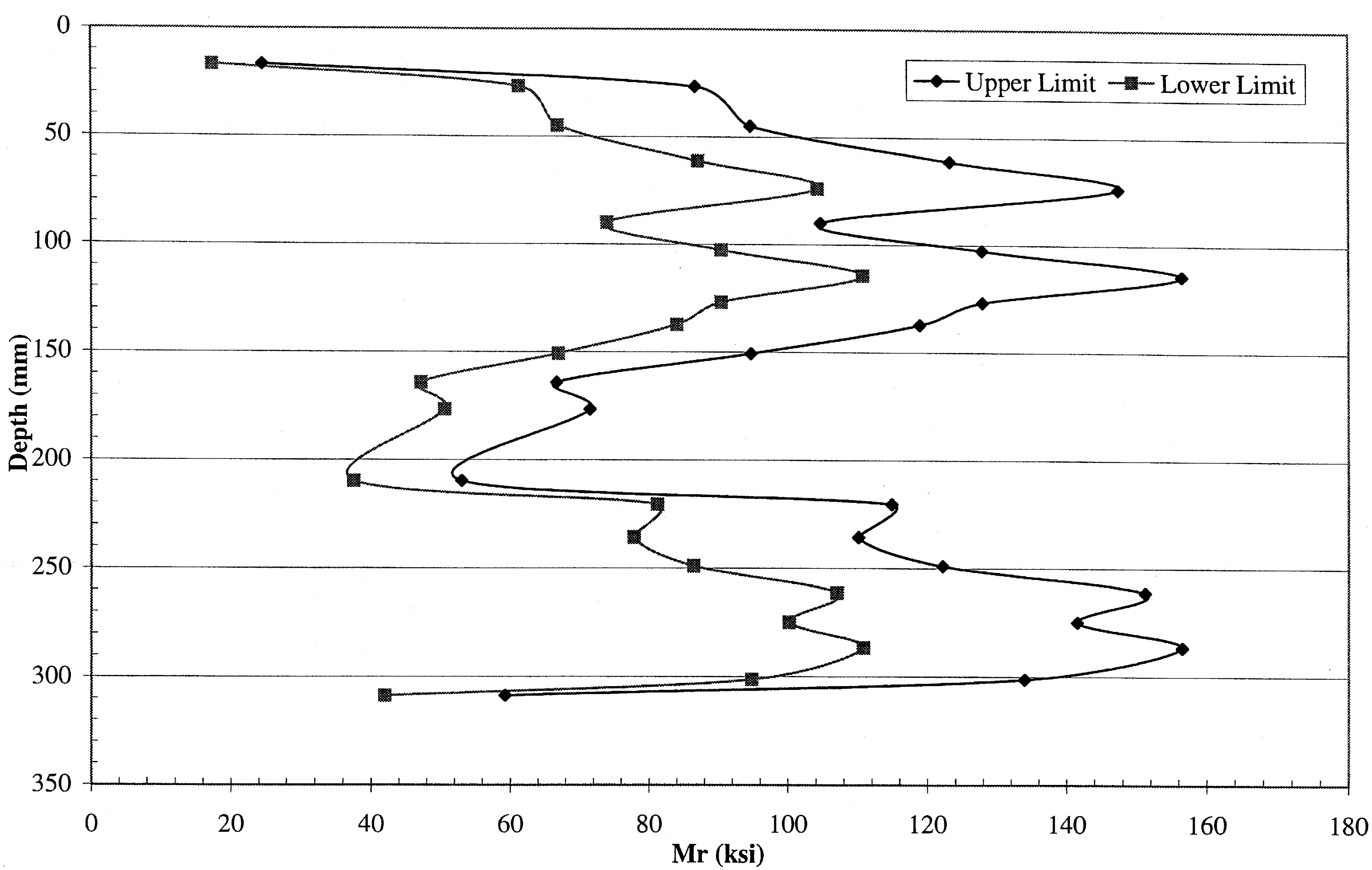

Figure E.18: Results of DCP Test on DGAB at Station 418+50

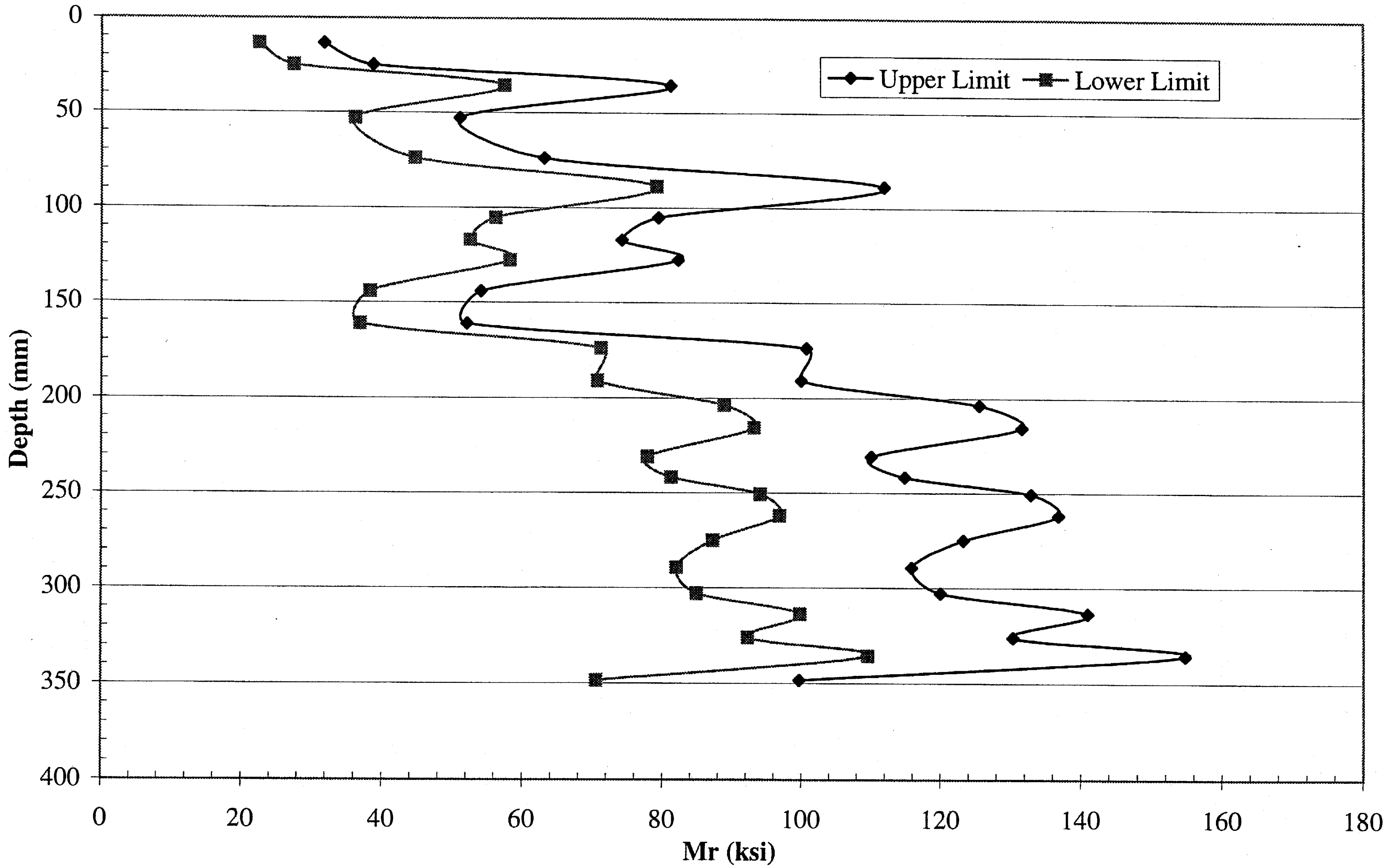

Figure E.19: Results of DCP Test on DGAB at Station 419+00

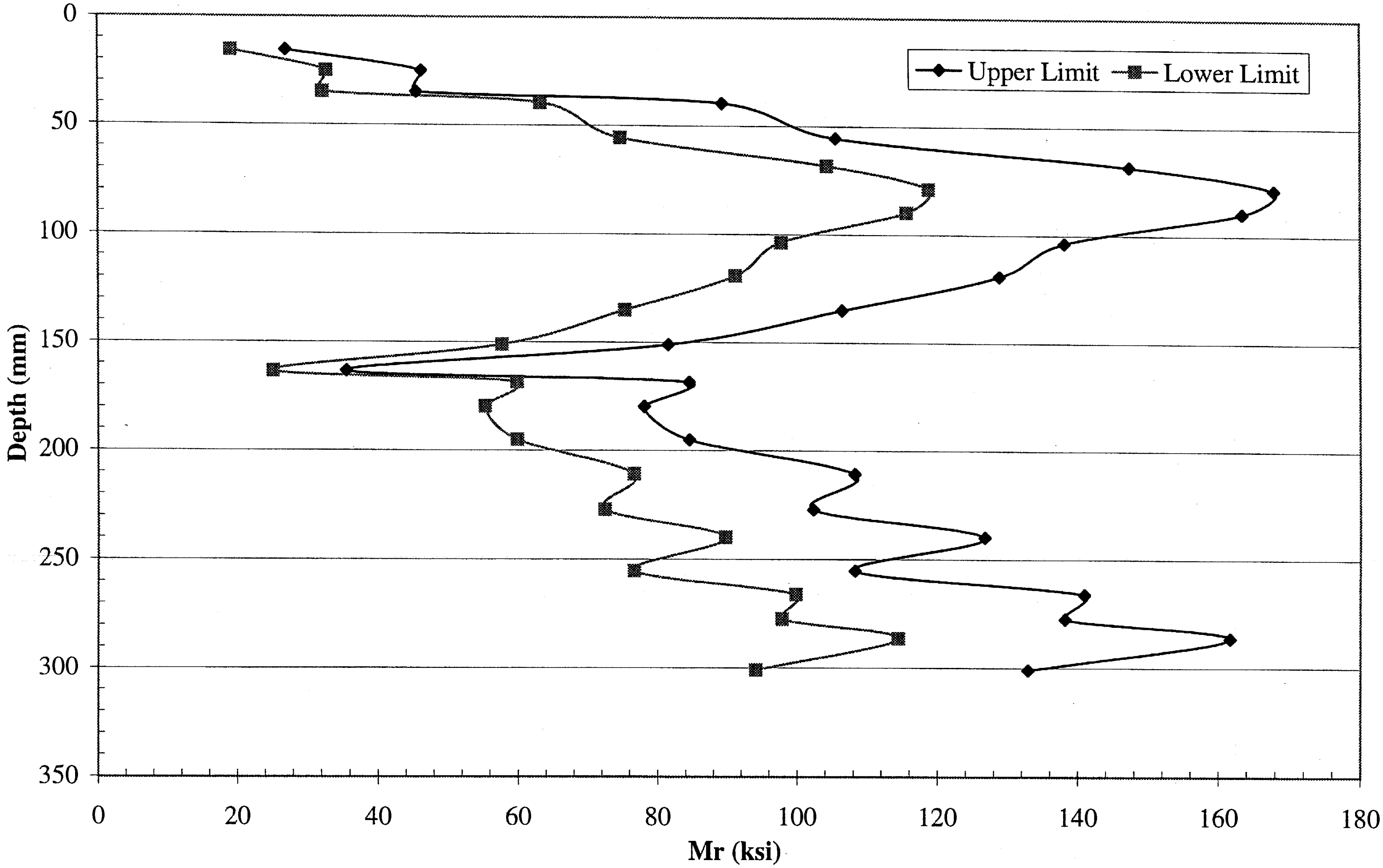

Figure E.20: Results of DCP Test on DGAB at Station 419+50

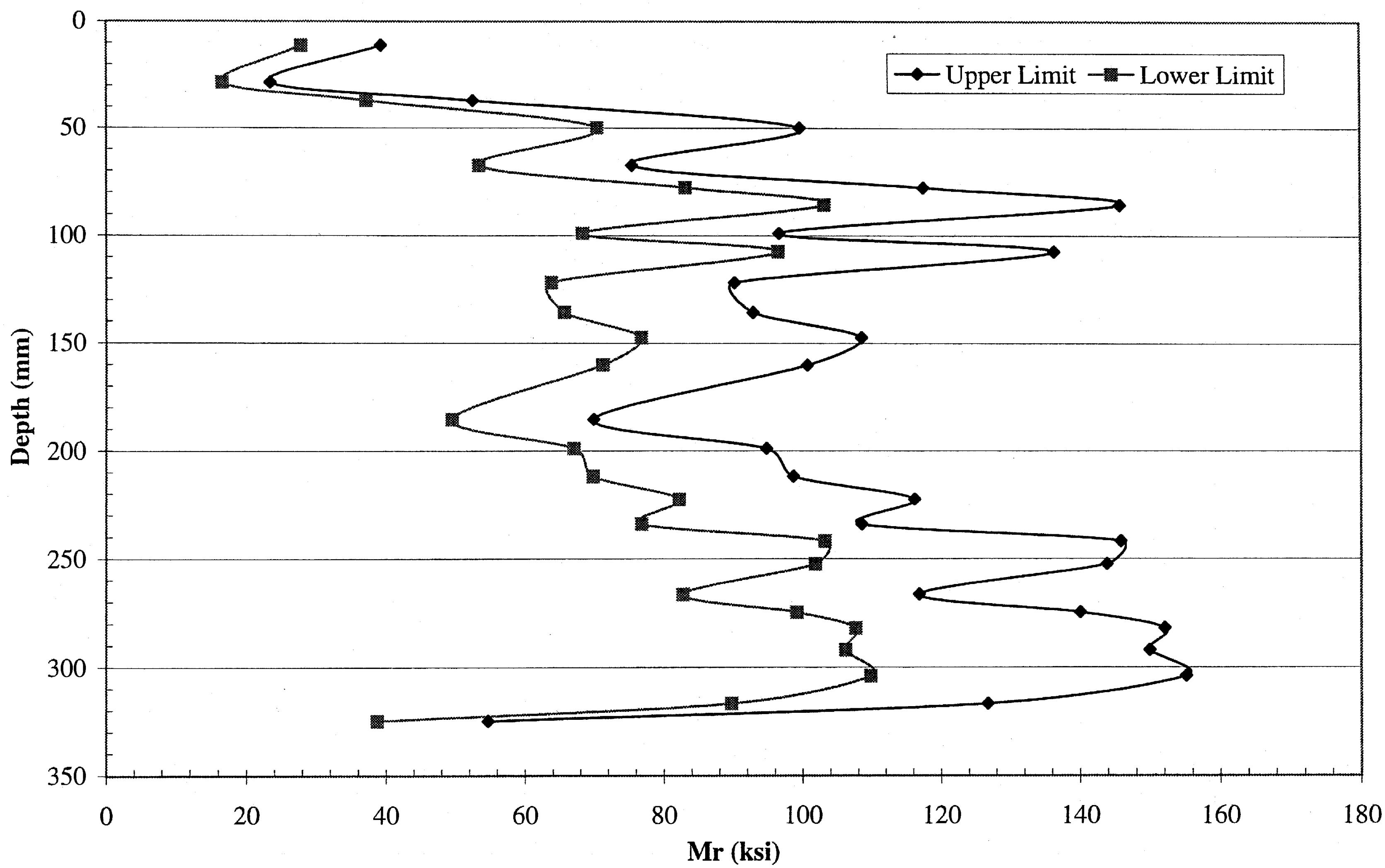

Figure E.21: Results of DCP Test on DGAB at Station 420+00

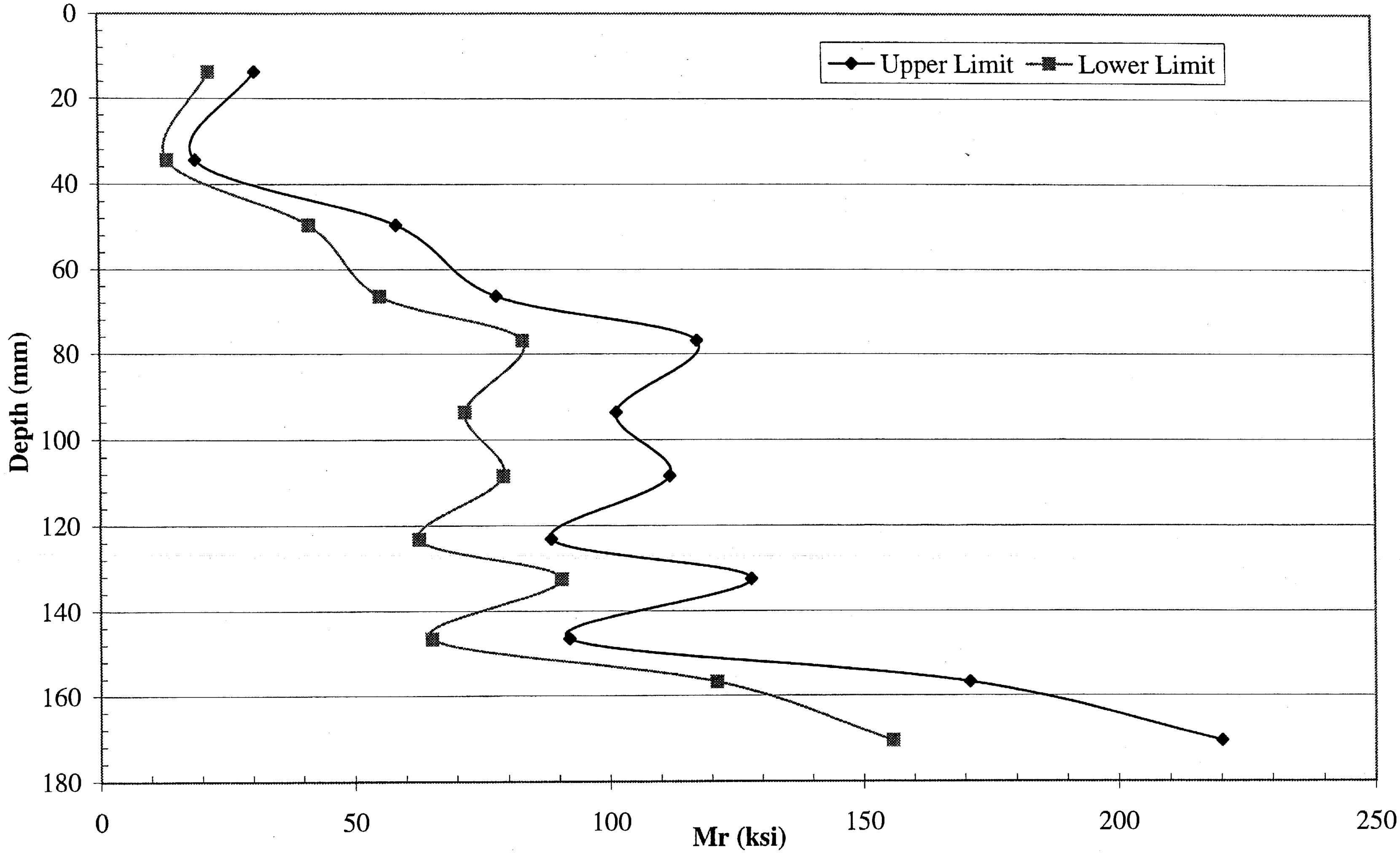

Figure E.22: Results of DCP Test on DGAB at Station 420+50

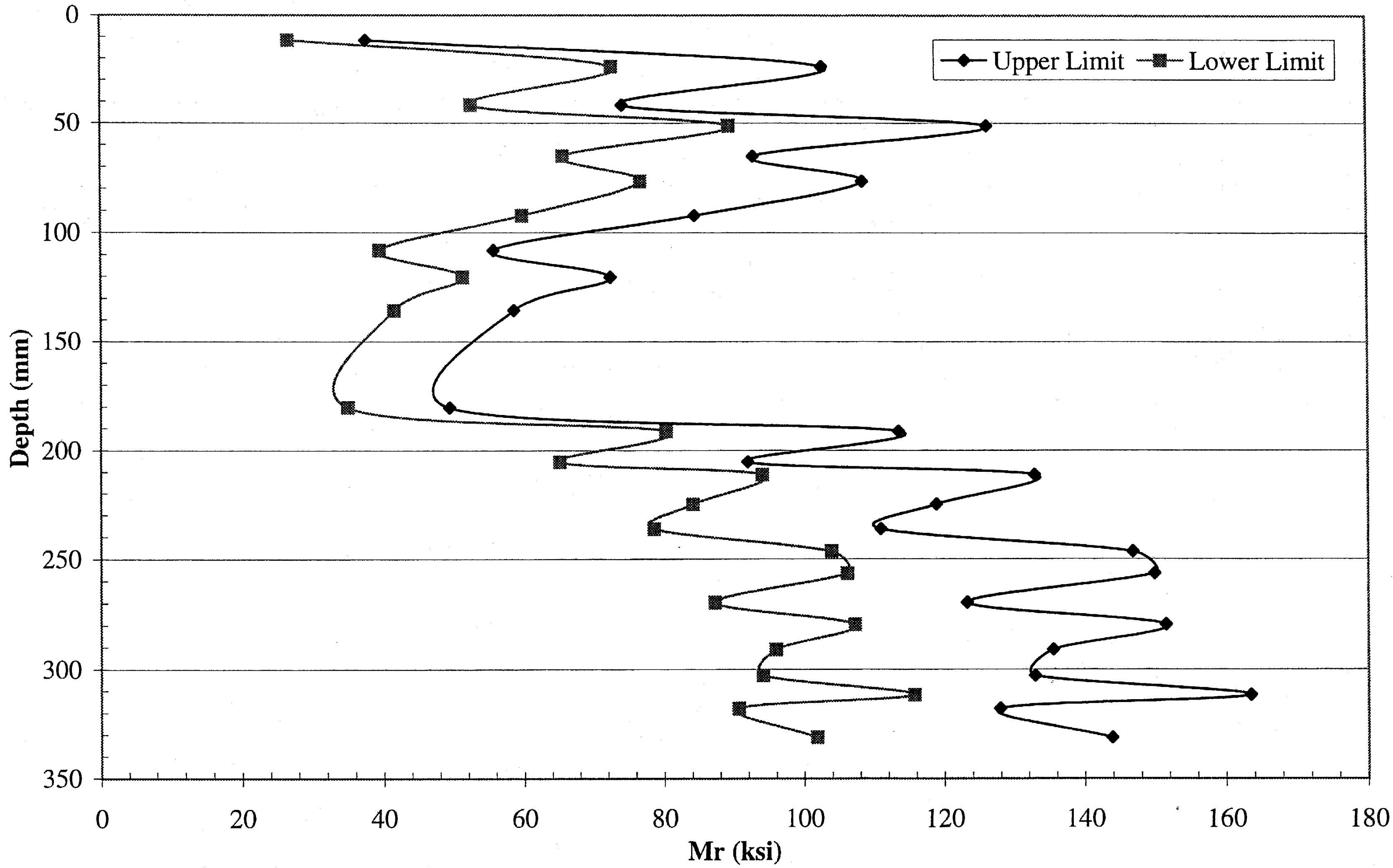

Figure E.23: Results of DCP Test on DGAB at Station 421+00

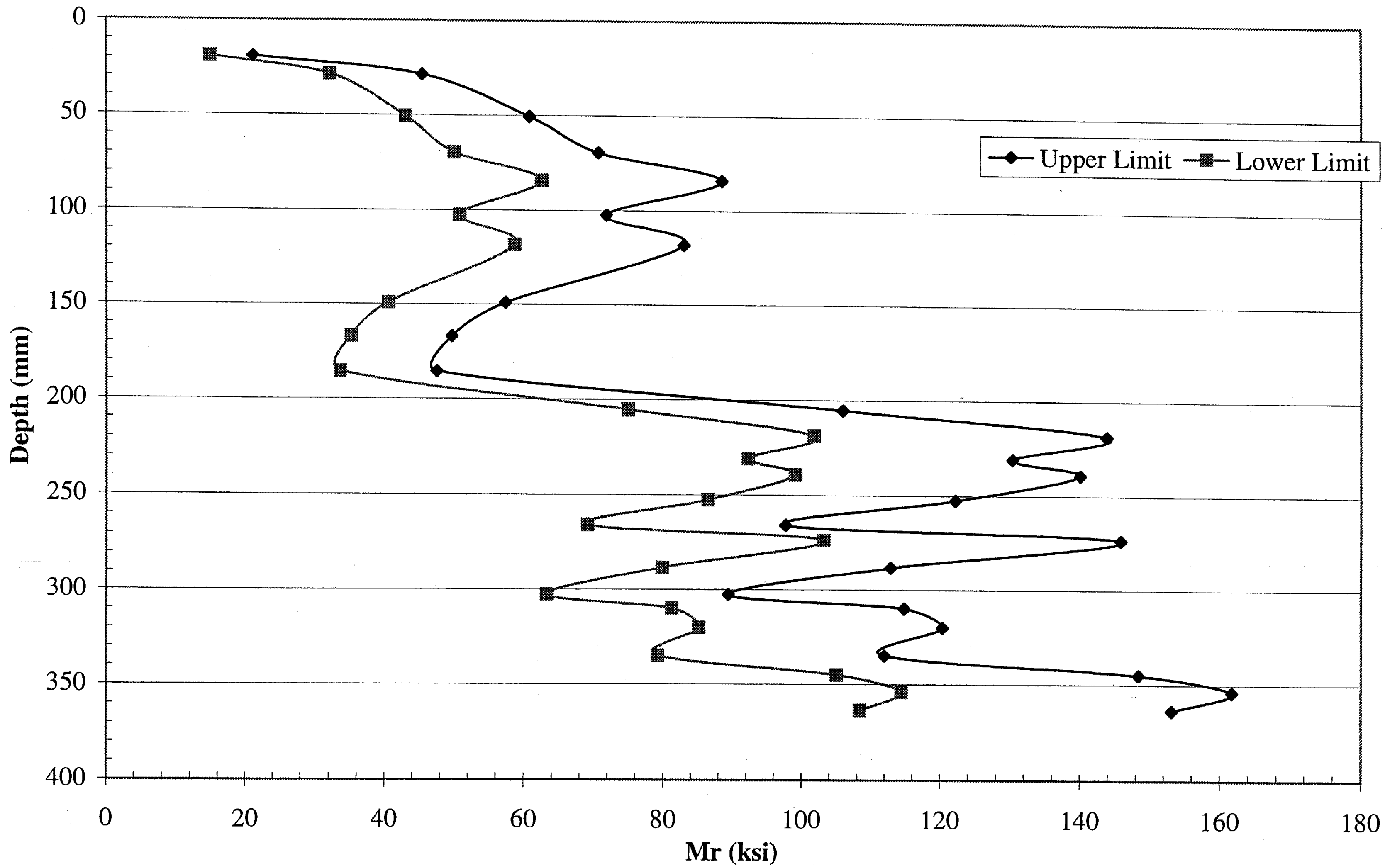

Figure E.24: Results of DCP Test on DGAB at Station 421+50

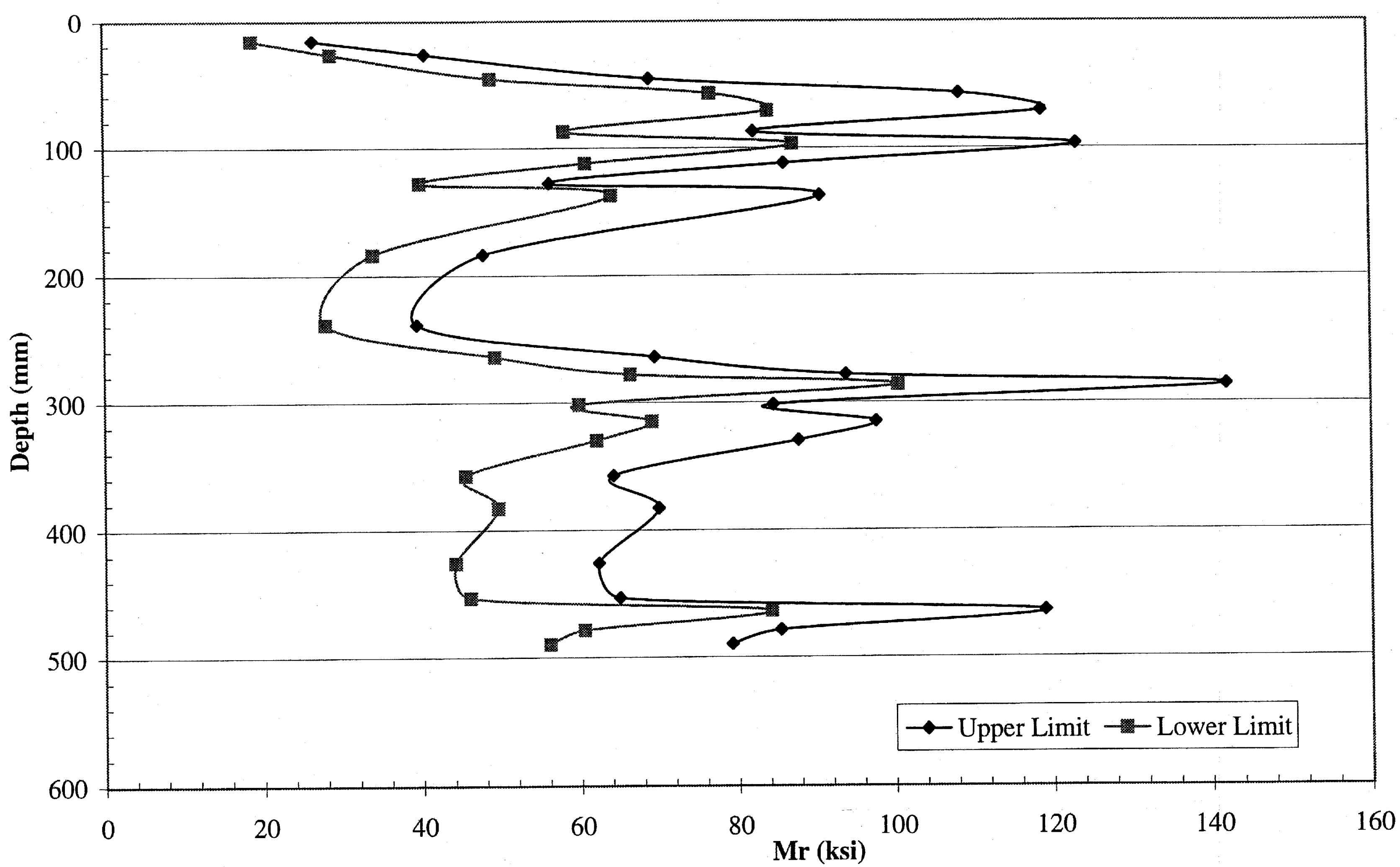

Figure E.25: Results of DCP Test on DGAB at Station 422+00

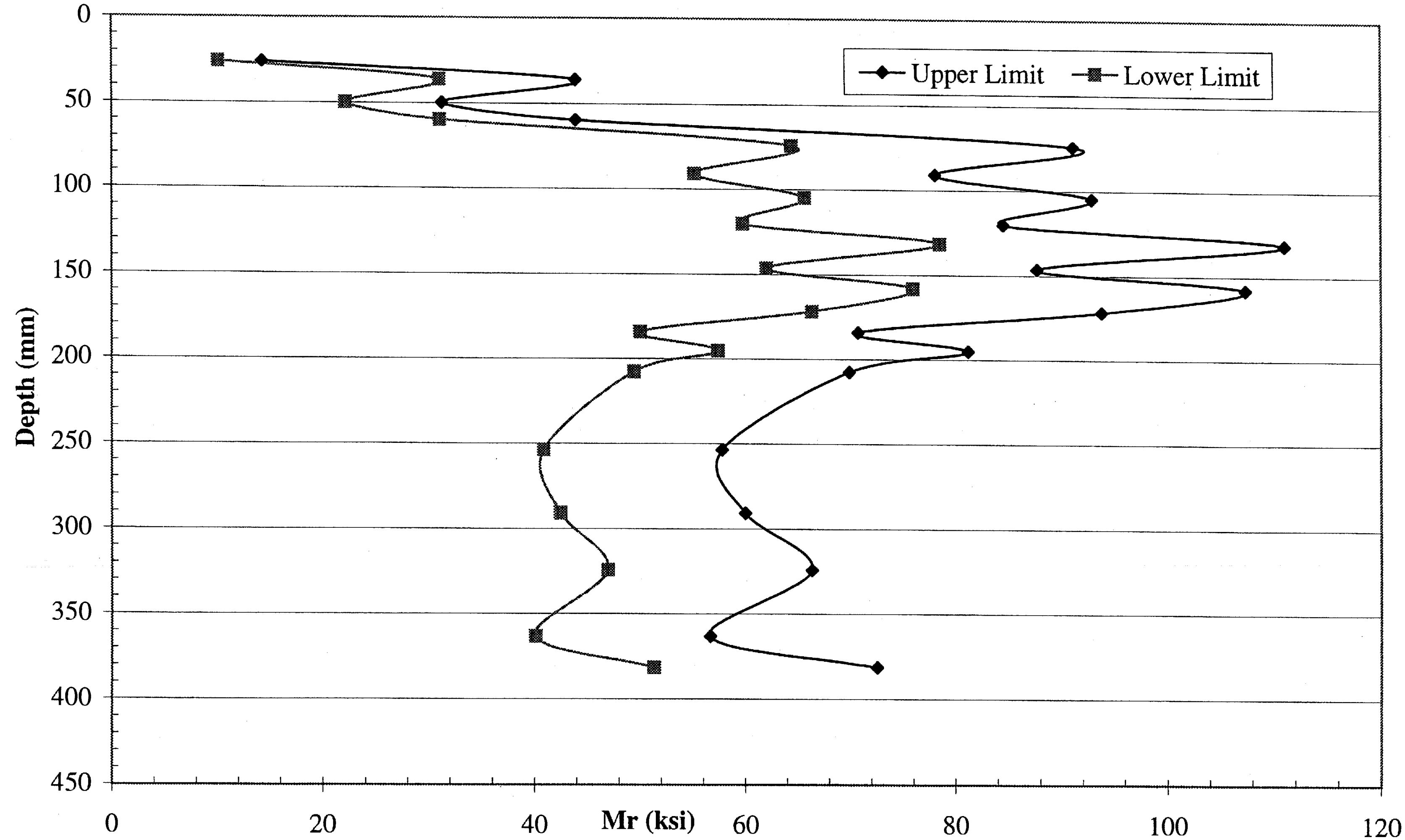

Figure E.26: Results of DCP Test on DGAB at Station 422+50

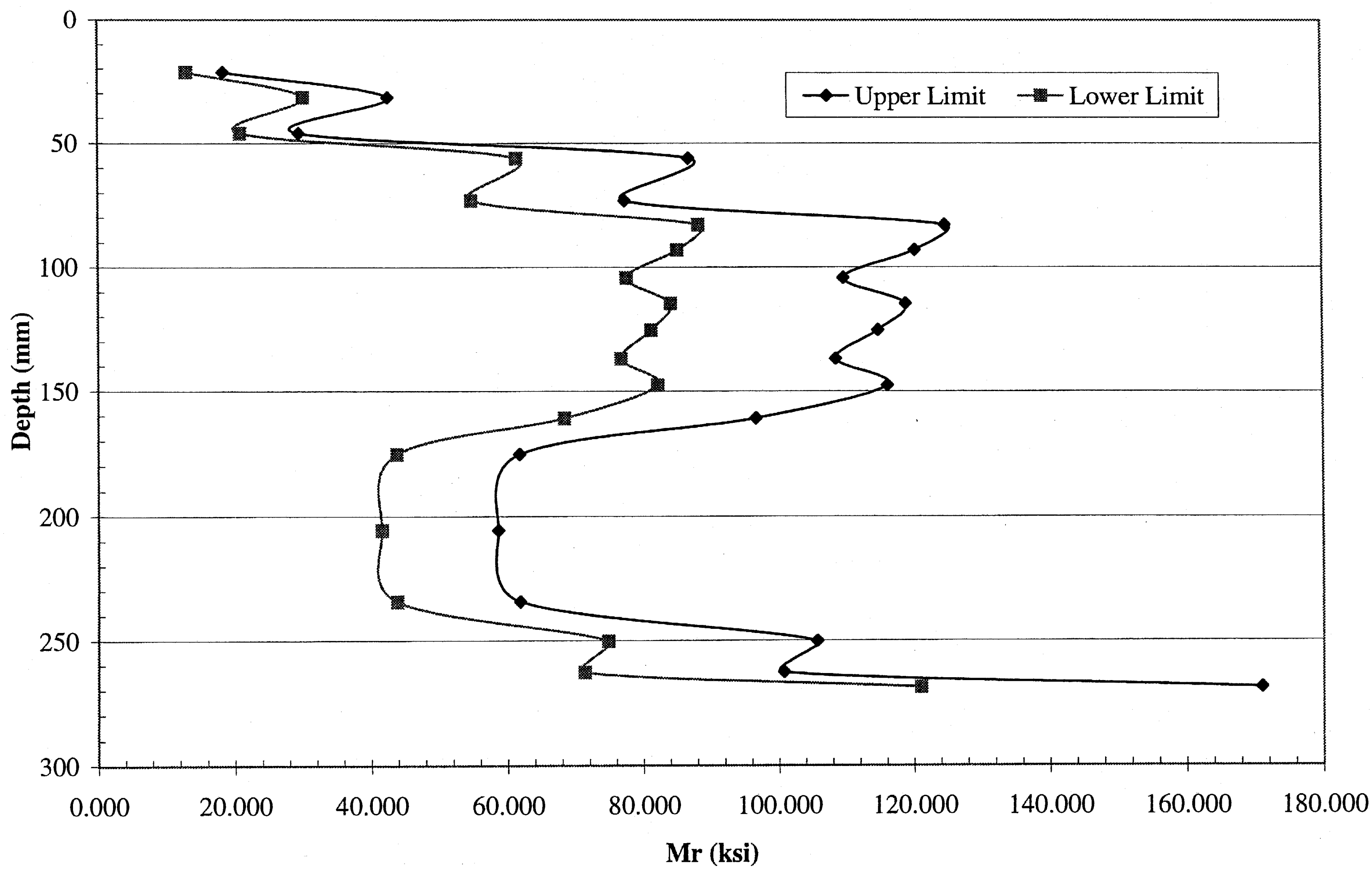

Figure E.27: Results of DCP Test on DGAB at Station 423+00

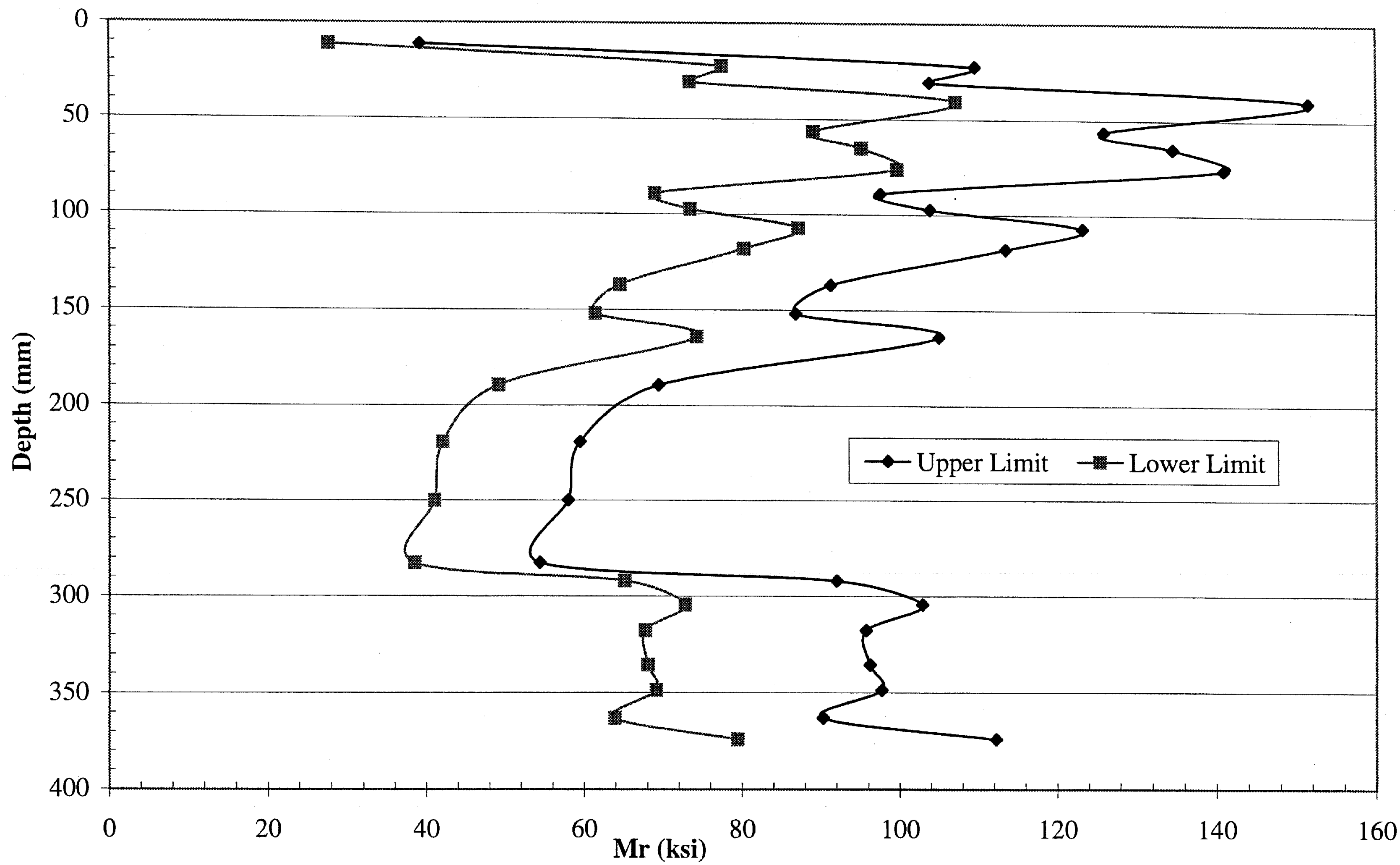

Figure E.28: Results of DCP Test on DGAB at Station 423+50

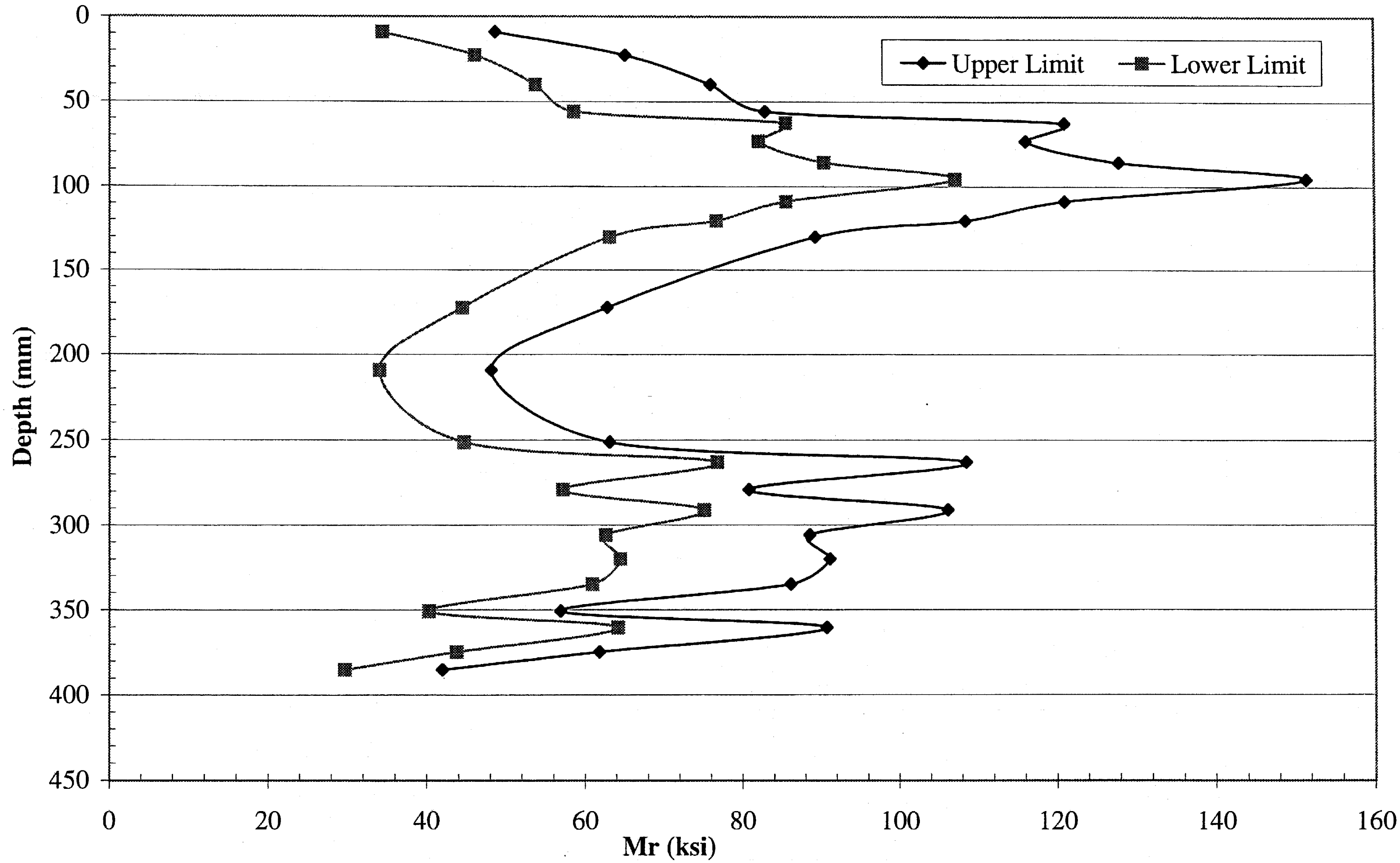

Figure E.29: Results of DCP Test on DGAB at Station 424+00

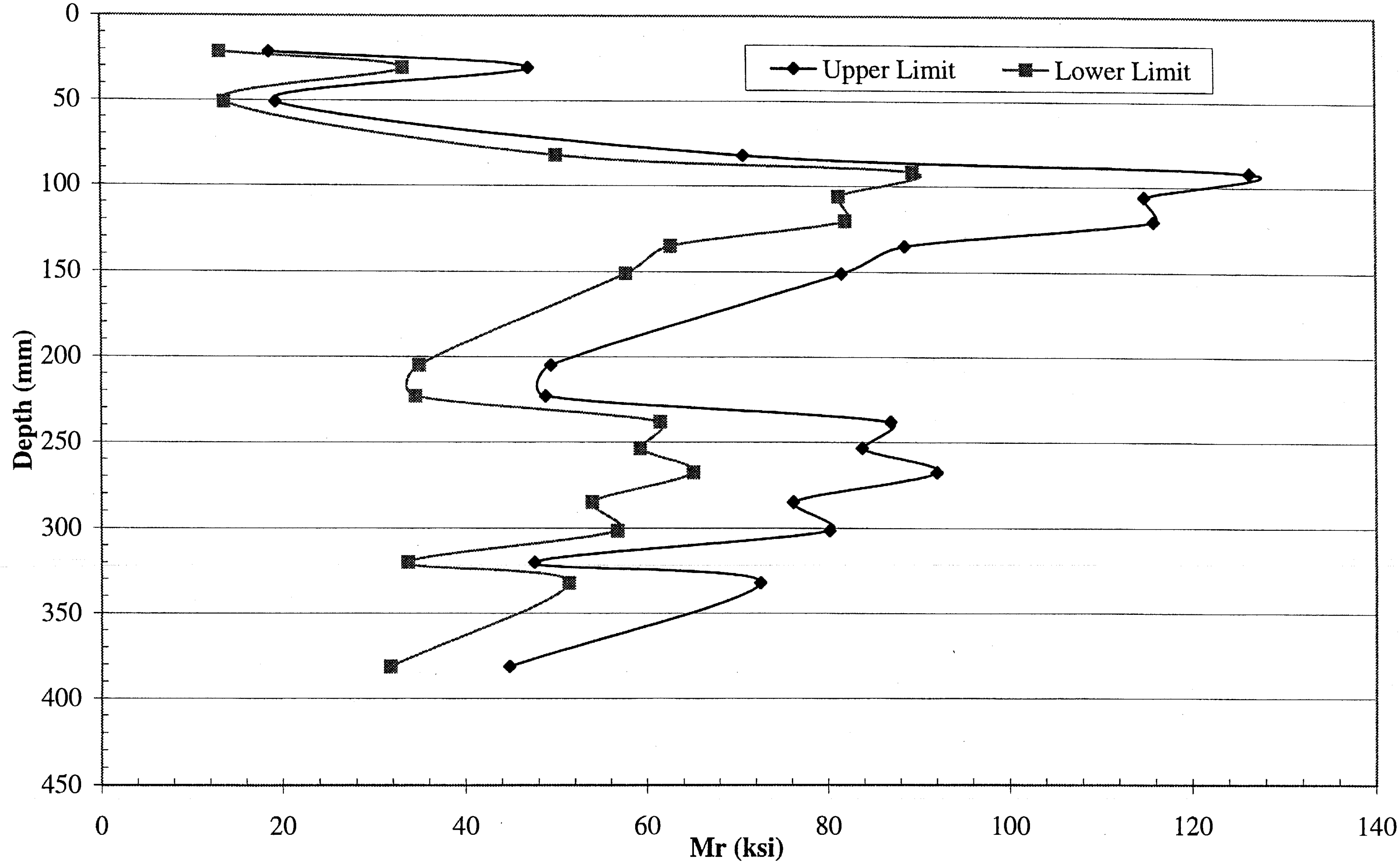

Figure E.30: Results of DCP Test on DGAB at Station 424+50

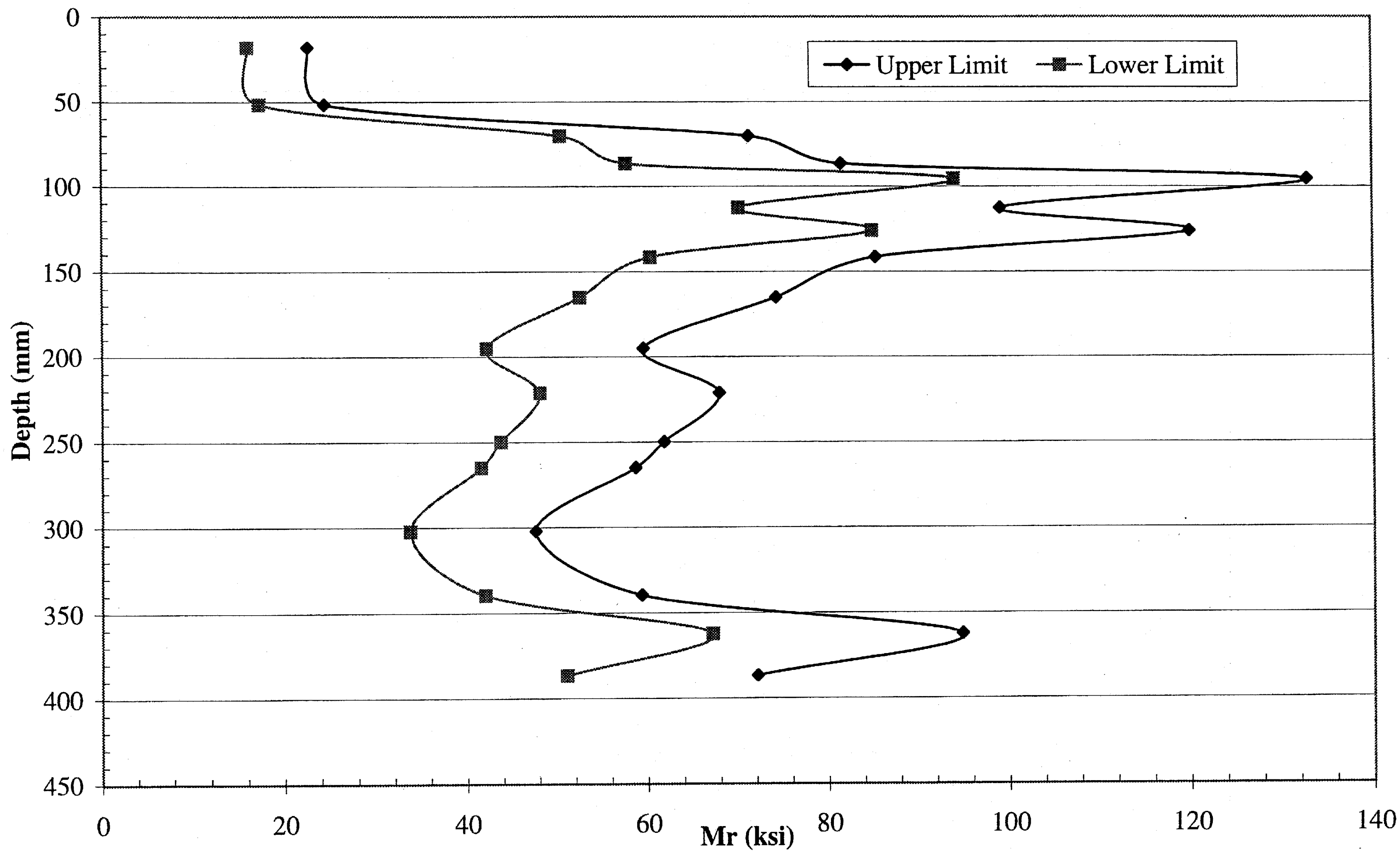

Figure E.31: Results of DCP Test on DGAB at Station 425+00

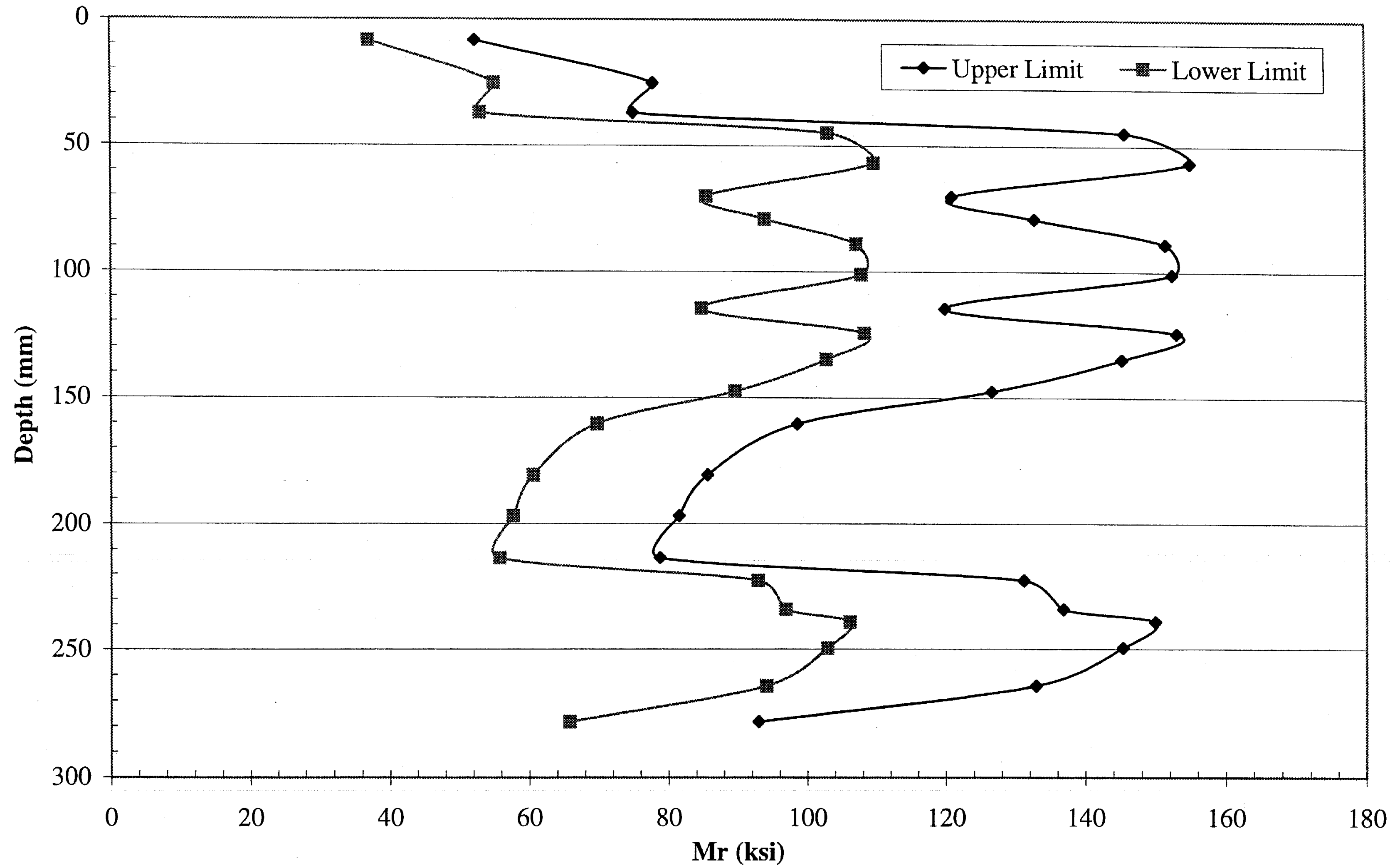

Figure E.32: Results of DCP Test on DGAB at Station 425+50

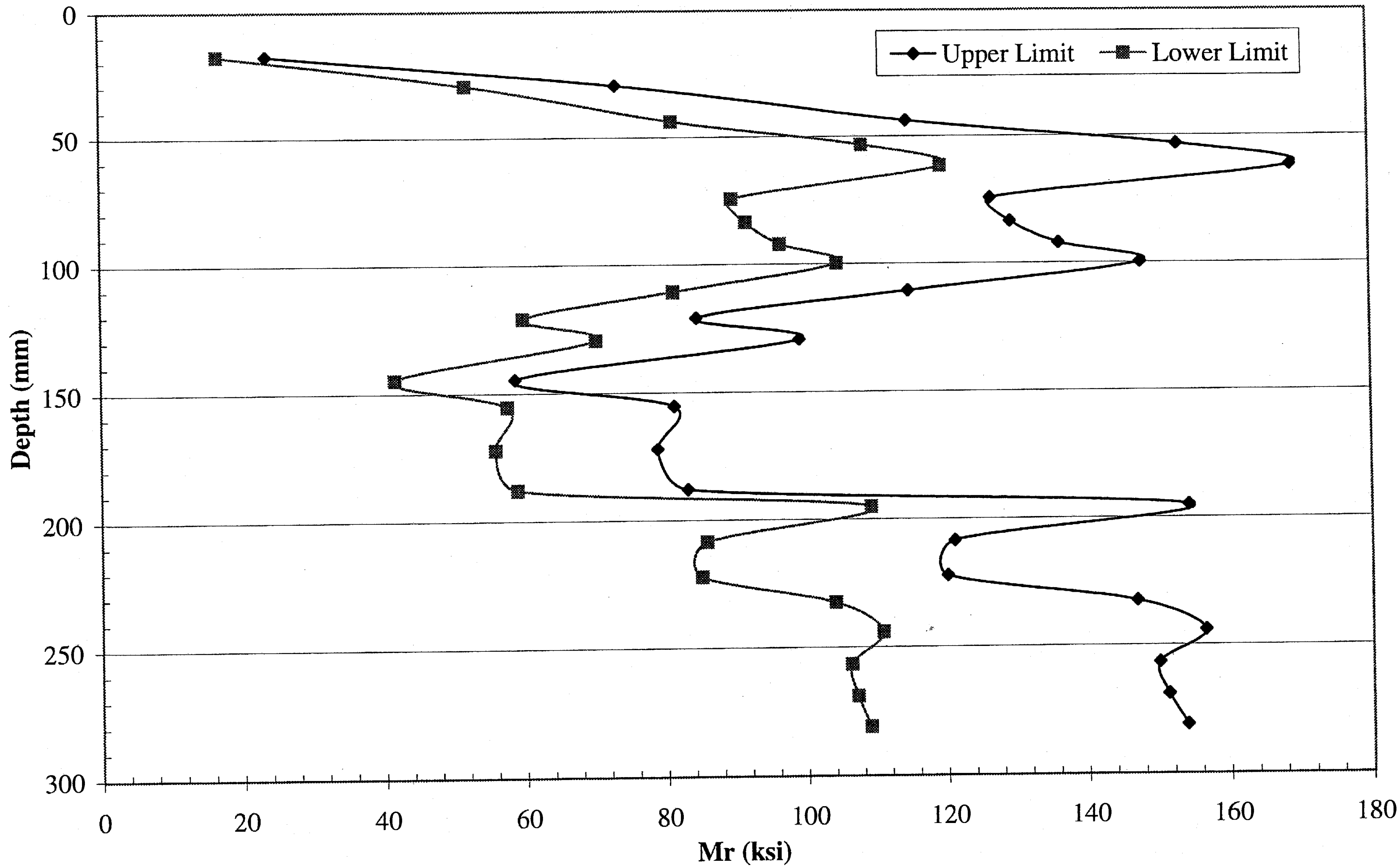

Figure E.33: Results of DCP Test on DGAB at Station 426+00

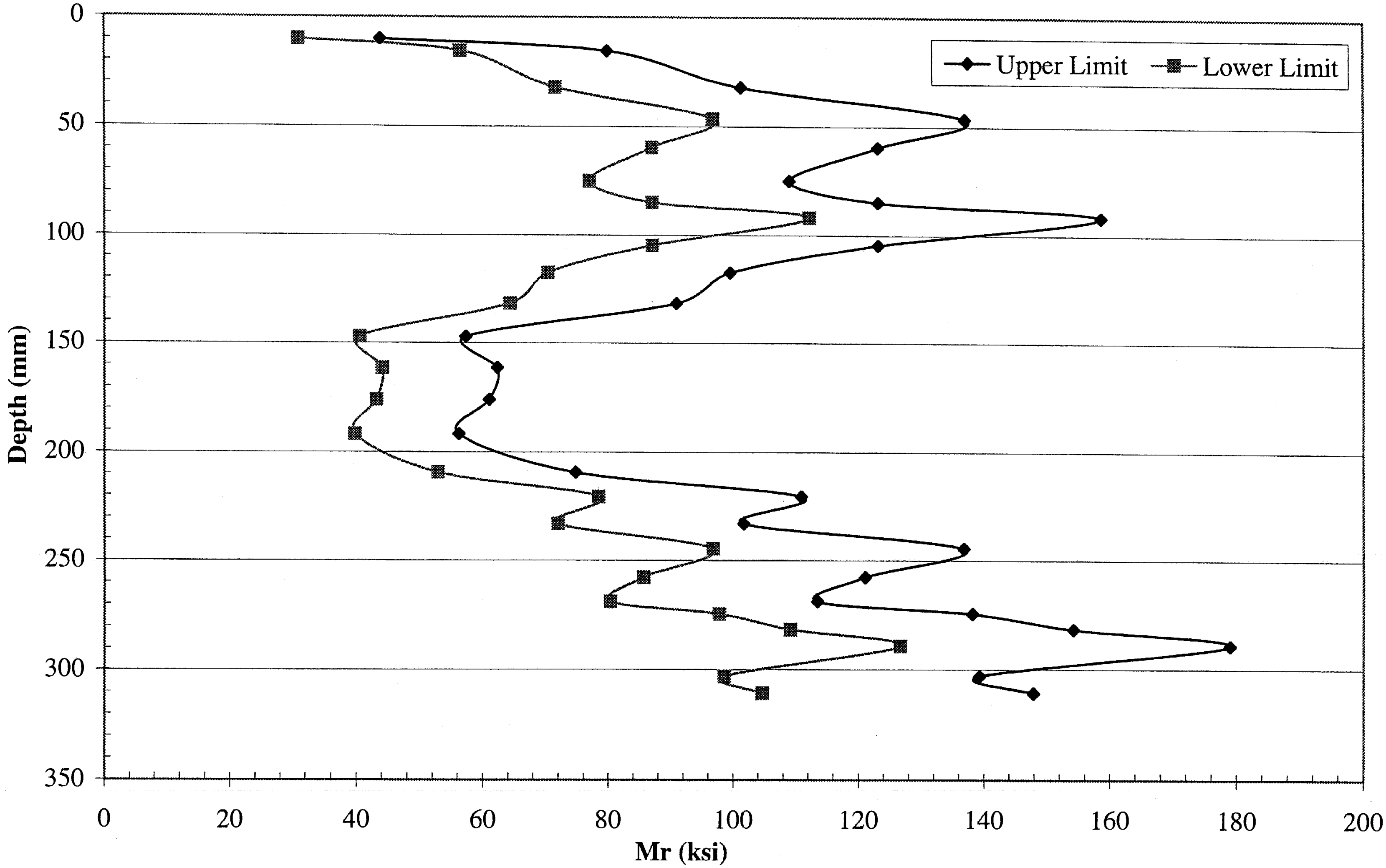

Figure E.34: Results of DCP Test on DGAB at Station 426+50

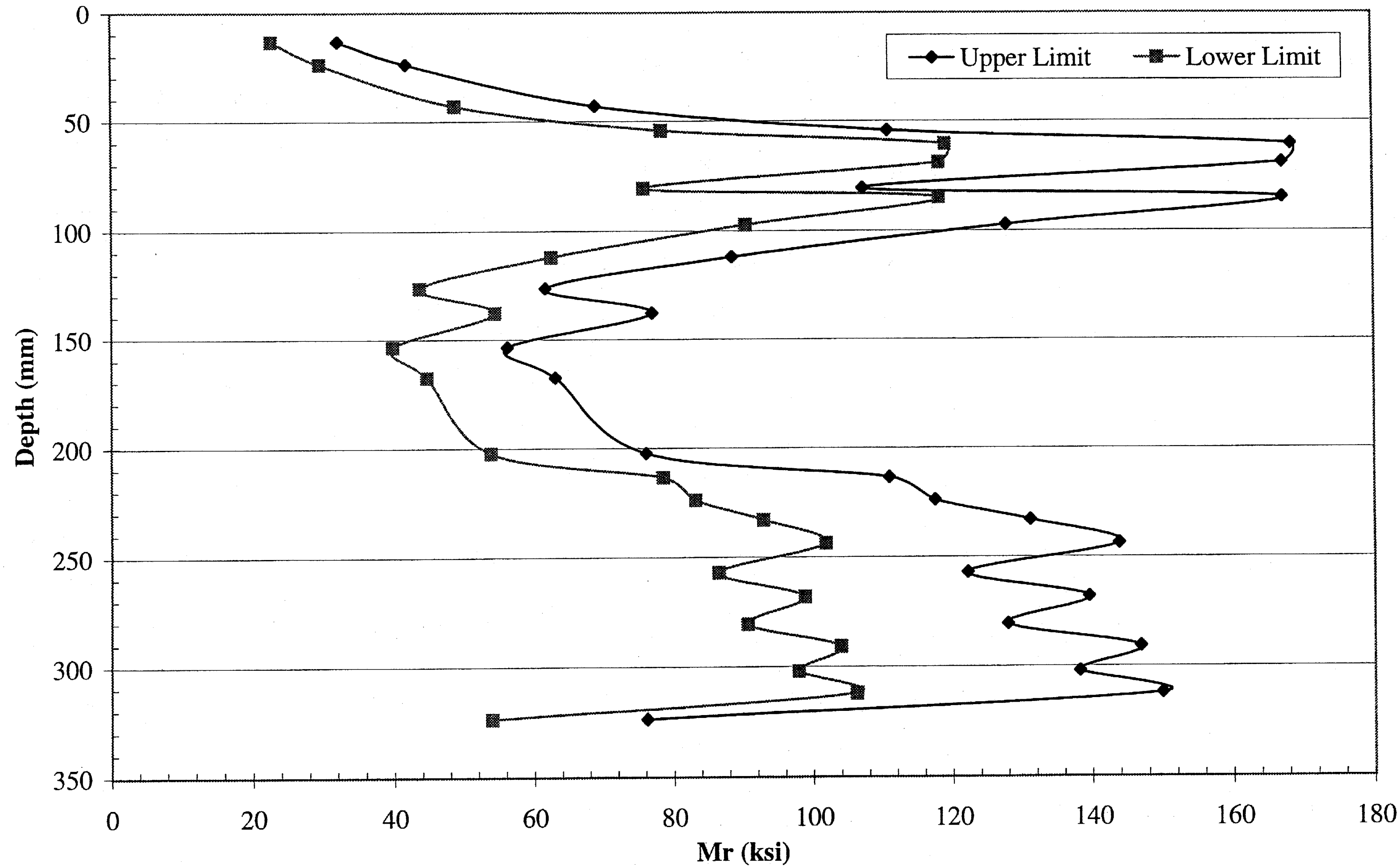

Figure E.35: Results of DCP Test on DGAB at Station 427+00

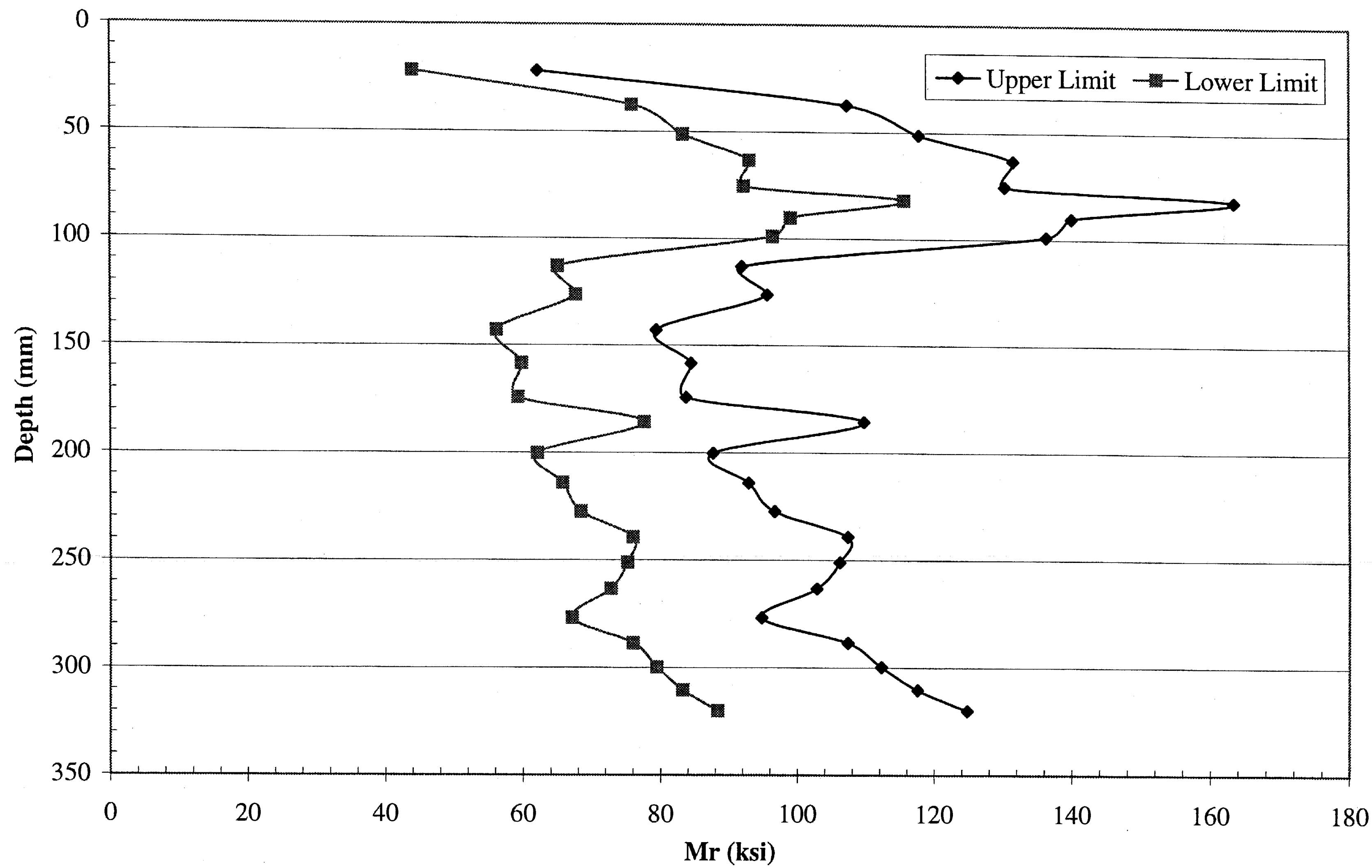

Figure E.36: Results of DCP Test on DGAB at Station 427+50

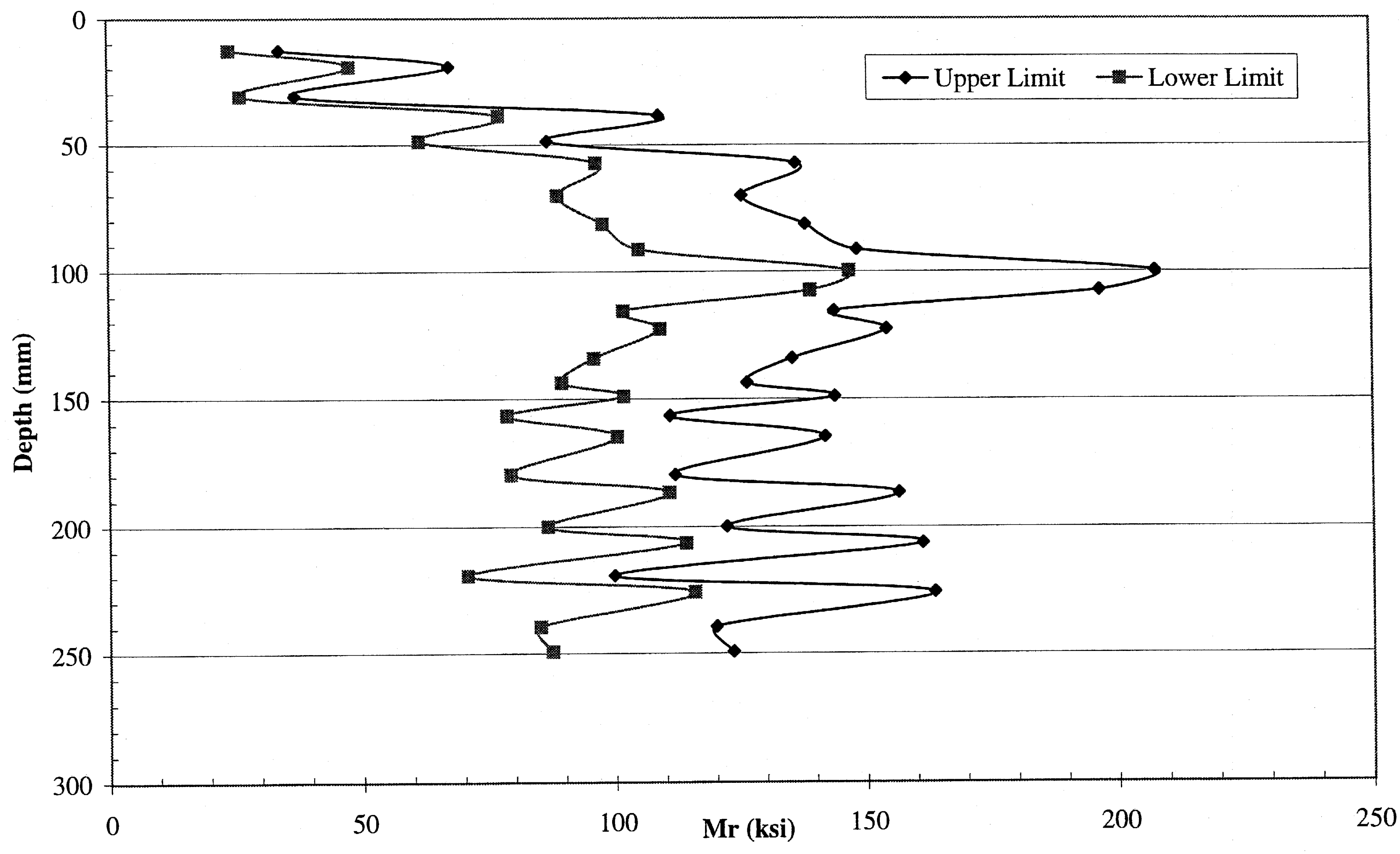

Figure E.37: Results of DCP Test on DGAB at Station 428+00

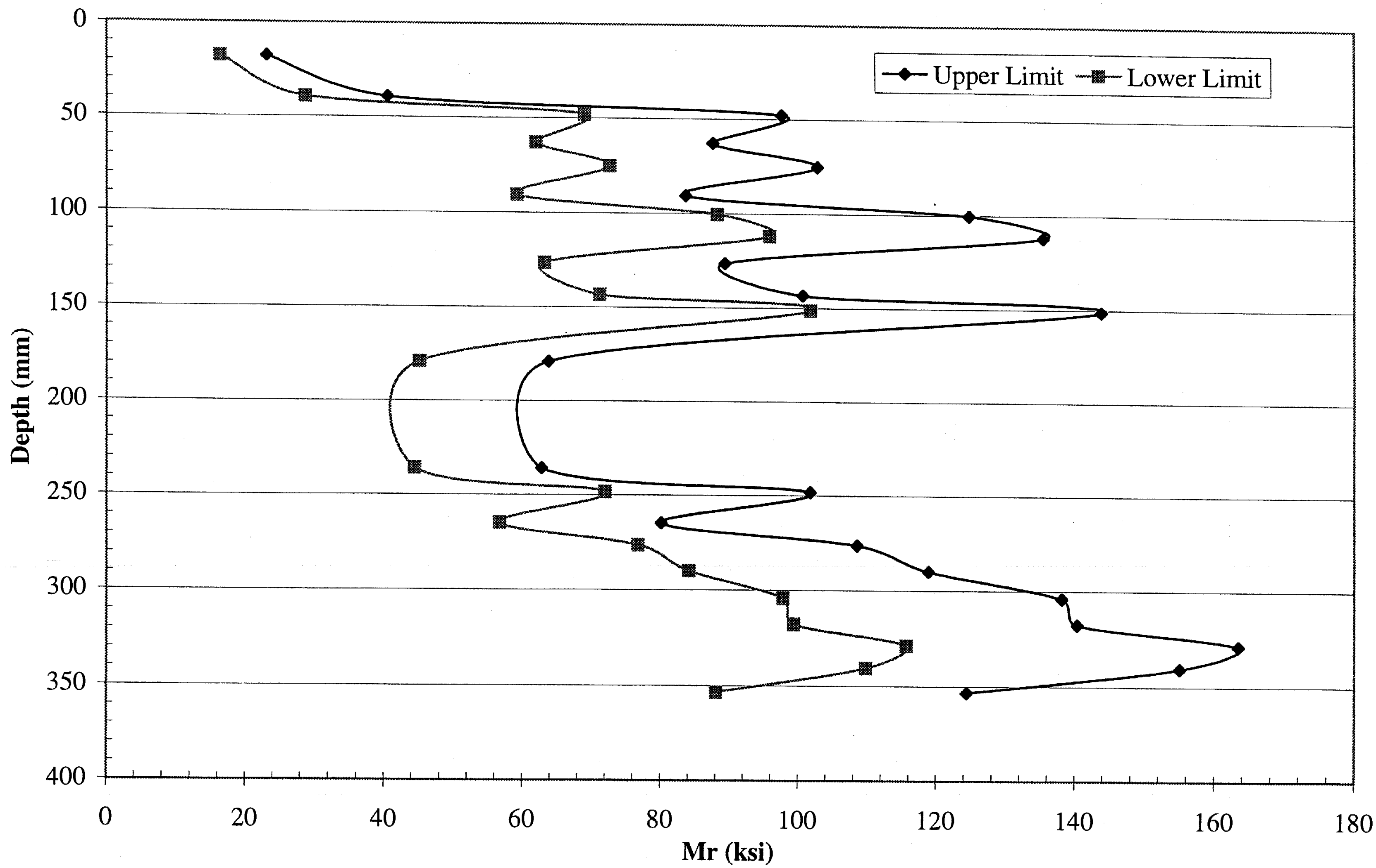

Figure E.38: Results of DCP Test on DGAB at Station 428+50

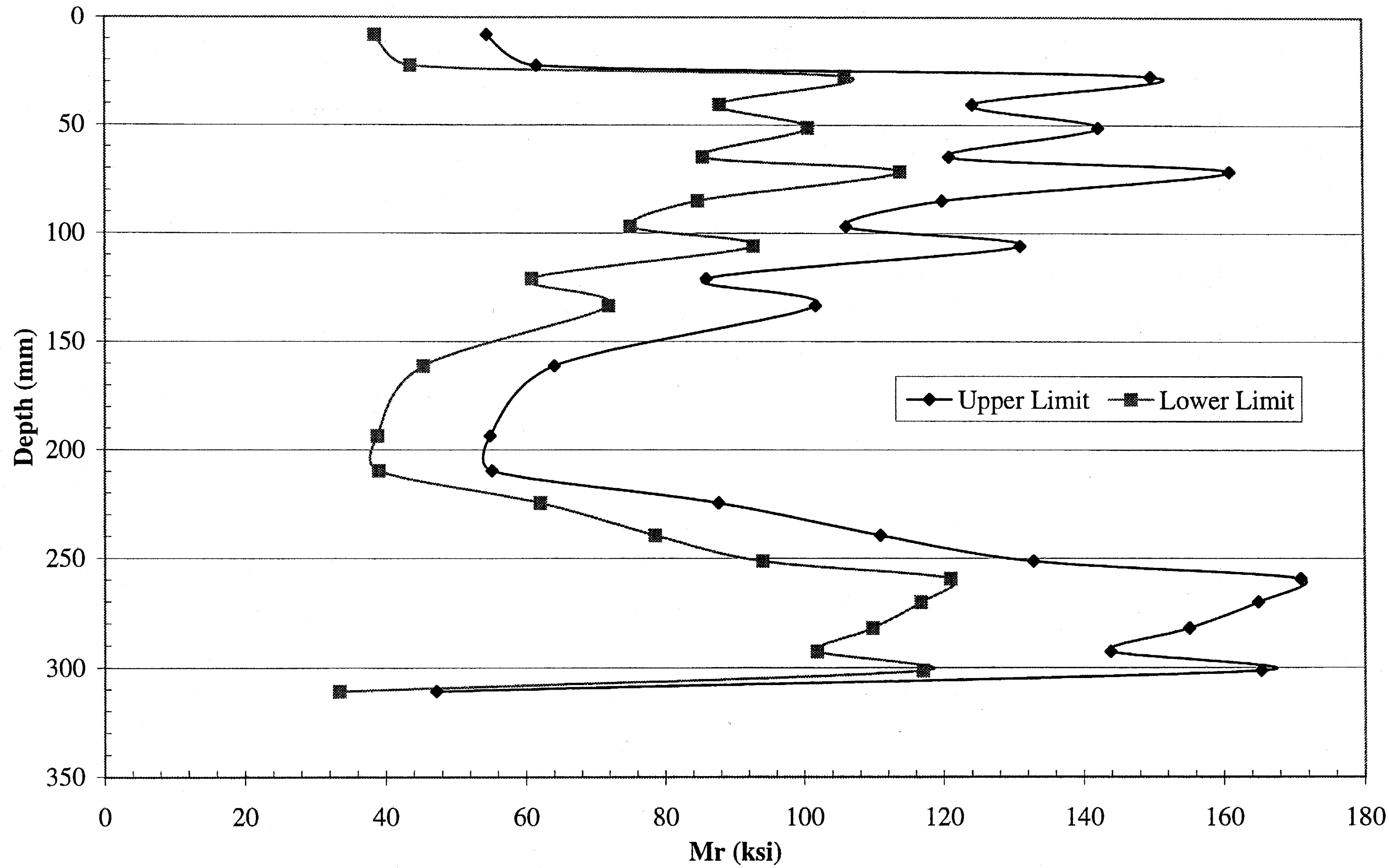

Figure E.39: Results of DCP Test on DGAB at Station 429+00

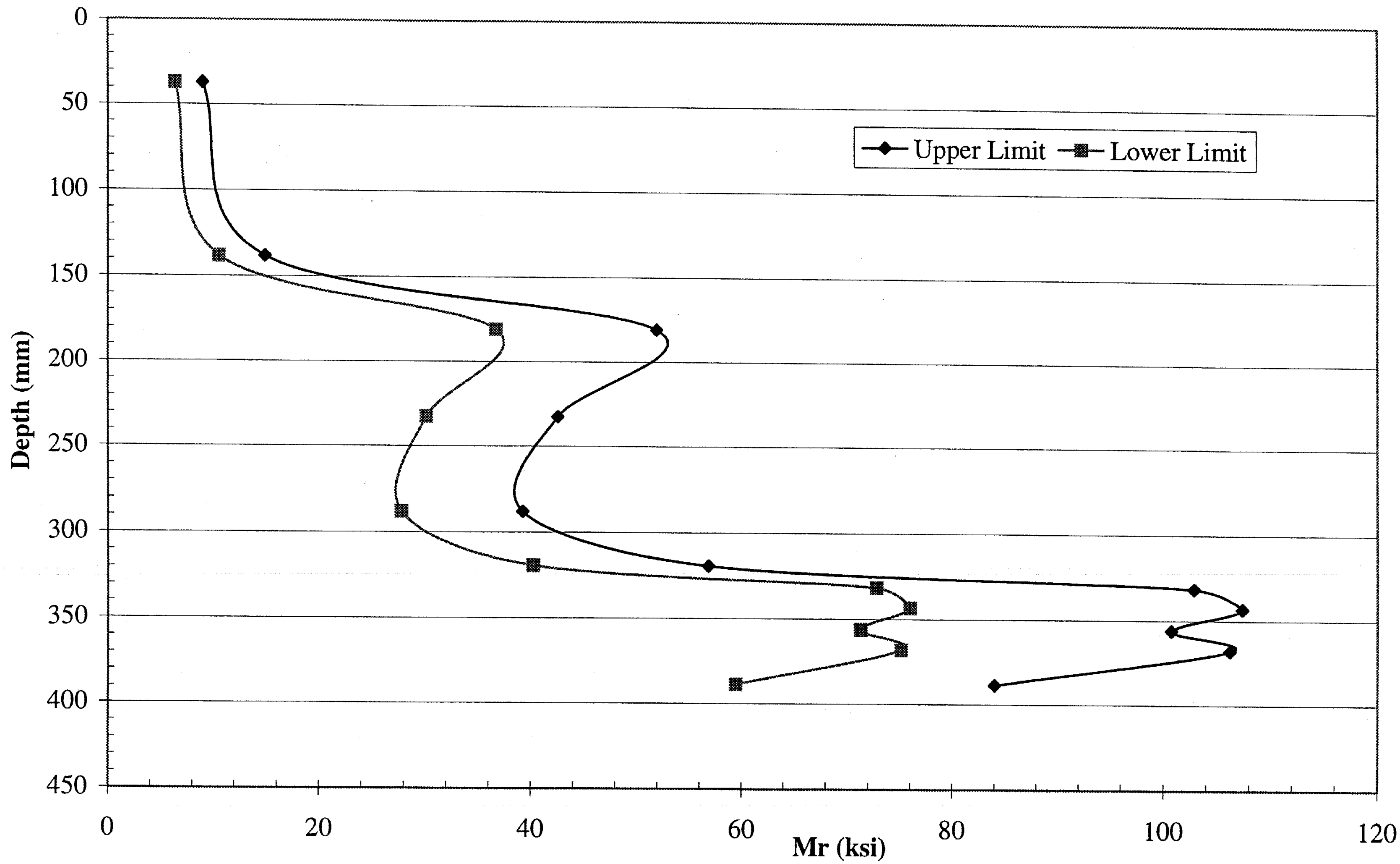

Figure E.40: Results of DCP Test on DGAB at Station 429+50

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